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# Co-Gasification of Densified Sludge and Solid Waste in a Downdraft Gasifier

California Univ., Davis

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# CO-GASIFICATION OF DENSIFIED SLUDGE AND SOLID WASTE IN A DOWNDRAFT GASIFIER

by

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Grant No. R-805-70-3010

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16. ABSTRACT

Thermal gasification, the subject of this report, is a new process for the co-disposal of densified sewage sludge and solid waste in a co-current flow, fixed bed reactor (also called a downdraft gasifier). The advantages of this technology include lower costs than other sewage sludge incineration of pyrolysis technologies, simple construction and the ability to use a variety of fuels including agriculture wastes and other biomass materials.

Essentially the gasification process involves the partial combustion of a carbonaceous fuel to generate a low energy combustible gas and a char. Operationally fuel flow is by gravity with air and fuel moving co-currently through the reactor. The low energy gas produced is primarily carbon monoxide, hydrogen and nitrogen and trace amounts of methane and other hydrocarbons.

Demonstrating that a suitable gasifier fuel could be made with a simple front end system consisting of source separation of solid waste, sludge dewatering, and fuel densification was an object of this project. The fuel cubes produced for this project were about equal in energy content to wood (Douglas Fir 21.05 MJ/kg, fuel cubes 19MJ/kg).

17. KEY WORDS AND DOCUMENT ANALYSIS

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|---|---|---|
| Sludge (sewage) disposal<br>Refusal disposal<br>Gasification<br>Char<br>Incineration<br>Pyrolysis<br>Biomass<br>Refuse separation<br>Solid fuel preparation | Gasifiers<br>Incinerators<br>Low BTU fuels<br>Solid fuels<br>Sludge and refuse co-disposal | 13B |

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## FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our national environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

Development of safe and economical methods for disposing of the sludges produced from wastewater treatment operations is one of the most pressing environmental needs. This publication provides much needed information on the feasibility of one approach to dispose of sludge and solid wastes which generates a gas that can be used to reduce the need for priority fuels.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

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## ABSTRACT

Thermal gasification, the subject of this report, is a new process for the co-disposal of densified sludge and solid waste in a co-current flow, fixed bed reactor (also called a downdraft gasifier). The advantages of this technology include lower costs than other incineration or pyrolysis technologies, simple construction and operation, and the ability to use a variety of fuels including agricultural wastes and other biomass materials in addition to densified sludge and solid waste. These and other related subjects are discussed in this report.

Essentially the gasification process involves the partial combustion of a carbonaceous fuel to generate a low energy combustible gas and a char. Operationally fuel flow is by gravity with air and fuel moving co-currently through the reactor. The low energy gas produced is composed primarily of carbon monoxide, hydrogen and nitrogen and trace amounts of methane and other hydrocarbons.

Although fixed bed gasifiers are mechanically simpler than other co-disposal reactors such as multiple hearth furnaces or mass fired incinerators, they have more exacting fuel requirements which include: 1) moisture content $\leq$ 20 percent, 2) ash content $\leq$ 6 percent, and 3) relatively uniform grain size. Neither municipal solid waste nor dewatered sludge meet these criteria without some front end processing. Demonstrating that a suitable gasifier fuel could be made with a simple front end system consisting of source separation of the solid waste, sludge dewatering, and fuel densification has been one of the objectives of this project.

To study the gasification process a pilot scale gasifier was constructed. A broad range of fuels have been tested with the gasifier including an agricultural residue, densified waste paper, and densified waste paper and sludge mixtures containing up to 25 percent sludge by wet weight. The sludge fuels were made from mixtures of lagoon dried primary and secondary sludge and recycled newsprint (in full scale systems a mixed paper fraction of solid waste would be used). The mixtures were densified using commercially available agricultural cubing equipment.

The gasifier was operated with each fuel, and measurements of the variables needed to characterize the process were made. Gas, fuel, and char analyses were used to compute energy balances. These data were used to calculate efficiencies for each run. Hot gas efficiency, which includes the sensible heat of the gas, ranged from 85.2 to 40.0 percent. The cold gas efficiency, which does not include the gas sensible heat, ranged from 37.1 to 80.7 percent. The dry, low energy gas produced during the tests ranged in higher heating value from 4.52 to 6.79 MJ/m$^3$.

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# CHAPTER I

# INTRODUCTION

Historically the civil engineer has been responsible for the protection of public health and safety through the design of wastewater treatment systems and solid waste disposal facilities. Originally the principal criterion placed on the civil engineer by the public was the safe disposal of liquid and solid wastes in the most economic manner possible.

Within the last decade, the public has demanded, and the government required, through Federal laws, that liquid and solid wastes be disposed of in a safe manner with minimum impact on the environment. In the environmental fervor of the day, cost-effectiveness was not always considered.

More recently it has become recognized that it is not enough to protect the environment. Systems for the disposal of liquid and solid wastes must also be both cost and energy effective. This concept has been codified into law, The Clean Water Act of 1977 (6). This law provides significant financial incentives to the states in the form of additional Federal cost sharing funds to encourage the use of innovative and/or alternate technology that is more cost effective and energy efficient than conventional technology. Similarly in the Resource Conservation and Recovery Act of 1976 (45) the focus of solid waste management was shifted from the disposal of solid wastes in landfills to the recovery of energy and the recycling of resources.

Today the co-disposal of sludge (the solid residues of wastewater treatment) and solid waste in a joint facility is acceptable from an environmental, economic, and energy standpoint. However, the trend in development of such projects has been towards very large systems. It has been assumed that the economics of scale precludes the use of such technology by small communities (less than 50,000 population).

This report presents the development of a new process for the co-disposal of sludge and solid waste, which unlike existing co-disposal technology, can be implemented on a small scale. The process involves the co-gasification of densified mixtures of sludge and source separated solid waste in a simple fixed bed reactor, also known as moving packed bed reactors (27,28). Energy, in the form of a low energy gas, which is produced by the process can be used to fuel boilers, heaters, engines, or turbines. The process is air-blown gasification which has been widely applied to coal, wood, and agricultural wastes, but has never before been used for the co-disposal of sludge and solid waste.

## PURPOSE OF PRESENT STUDY

This study was undertaken to 1) review existing co-disposal technology, 2) assess the potential for small scale co-disposal and energy recovery, 3) explore the feasibility of utilizing gasification technology in small communities, 4) design and construct a pilot scale co-gasification system, 5) present and analyze data from co-gasification experiments, 6) compare the economics of co-gasification with conventional sludge disposal techniques, and 7) discuss how gasification technology can be best implemented in an integrated waste management system for small communities.

## CITED LITERATURE

Cited reports, studies, and other pertinent literature have been arranged alphabetically and numbered sequentially, and may be found at the end of this report. Where reference is made to this material in the text, the appropriate number or numbers are enclosed in parentheses.

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# CHAPTER II

# BACKGROUND

The treatment of wastewater, disposal of wastewater sludges, and collection and disposal of municipal solid wastes are public works functions that should be considered in an integrated fashion. All of these activities are energy intensive and must be accomplished to protect both the public health and the environment. However if the energy contained in municipal solid waste could be recovered and converted to a usable form, it could subsitute for much of the energy consumed in the treatment of wastewater and disposal of sludges.

Conventional methods for sludge and solid waste disposal are reviewed in this chapter. The co-disposal of sludge and solid waste is also considered. Finally a new concept for co-disposal, the co-gasification of densified mixtures of source separated solid waste and sludge is presented.

## CONVENTIONAL APPROACHES TO SLUDGE DISPOSAL

Sludge is the liquid or semi-liquid byproduct of wastewater treatment. Typically the solids content of sludge ranges from 0.25 to 12 percent solids, depending on the wastewater treatment process used. Dealing with sludge is complex and expensive because it is composed of the solid constituents present originally in the wastewater (primary sludge) and the organic matter contained in the wastewater converted to bacterial cell tissue (biological sludge). Current sludge disposal practices are reviewed in the following discussion.

### Unit Operations of Sludge Processing and Disposal

The ultimate purpose of sludge processing is to dispose of sludge in as economic and environmentally benign a manner as possible. To accomplish this goal, many unit operations and processes are available. The principal unit operations and processes used in sludge management are summarized in Table 1.

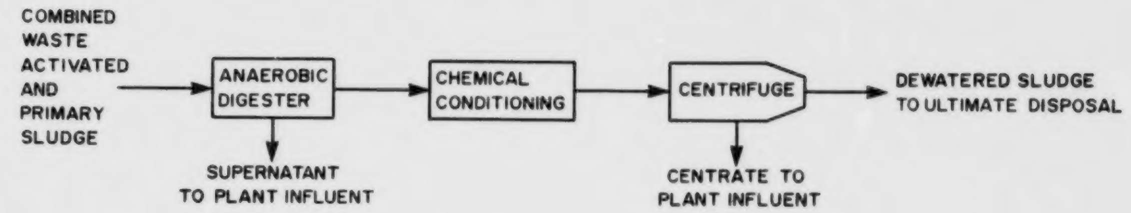
### Typical Sludge Treatment Flowsheets

The unit operations and processes mentioned in Table 1 can be assembled in an almost infinite variety of flowsheets. In general, two basic catagories of flowsheets can be formulated, biological systems in which aerobic or anaerobic digestion is used to stabilize sludge, and thermal systems in which incineration or pyrolysis, thermal gasification, or liquefaction (PTGL) processes are used to reduce the volume and sterilize the sludge. Typical flowsheets for each category are shown in Figure 1.

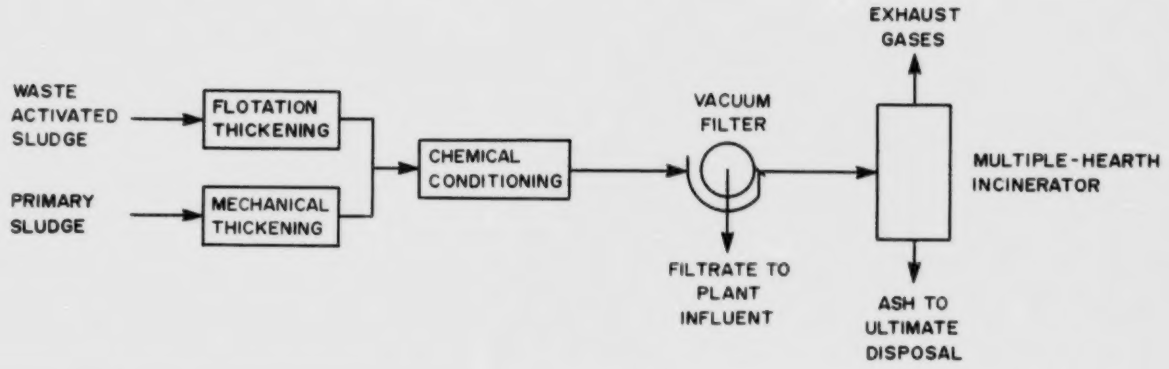
## Table 1
## SUMMARY OF UNIT OPERATIONS AND PROCESSES FOR SLUDGE TREATMENT AND DISPOSAL

| Unit Operation or Process | Function | Typical Process or Operation |
|---|---|---|
| Thickening | Volume reduction to increase the efficiency of downstream processes | Flotation and gravity thickeners, centrifuges |
| Stabilization | Pathogen destruction, volume and weight reduction, odor control | Chlorine oxidation, lime stabilization, heat treatment, anaerobic digestion, aerobic digestion |
| Conditioning | Improvement of dewatering or thickening rate, improvement of solids capture, improvement of compaction, stabilization | Chemical conditioning, elutriation, heat treatment |
| Dewatering | Water removal, volume and weight reduction, reduction of fuel requirements for incineration/drying | Vacuum filter, filter press, horizontal belt filter, centrifuge, drying bed, lagoon |
| Drying | Water removal, sterilization, utilization | Flash dryer, spray dryer, rotary dryer, multiple hearth dryer, oil emersion dehydration |
| Composting | Pathogen reduction, volume reduction, product recovery | Composting (sludge only), co-composting with solid waste |
| Thermal reduction | Destruction of solids, water removal, sterilization, energy recovery | Multiple hearth incinerator, fluidized bed incinerator, flash combustion, pyrolysis-thermal gasification-liquification (PTGL) processes, co-disposal with solid wastes |
| Ultimate disposal | Utilization and disposal | Sanitary landfill, land application, land reclamation |

Adapted from References 33 and 41


COMBINED WASTE ACTIVATED AND PRIMARY SLUDGE
ANAEROBIC DIGESTER
SUPERNATANT TO PLANT INFLUENT
CHEMICAL CONDITIONING
CENTRIFUGE
CENTRATE TO PLANT INFLUENT
DEWATERED SLUDGE TO ULTIMATE DISPOSAL

a) Biological


WASTE ACTIVATED SLUDGE
PRIMARY SLUDGE
FLOTATION THICKENING
MECHANICAL THICKENING
CHEMICAL CONDITIONING
VACUUM FILTER
FILTRATE TO PLANT INFLUENT
EXHAUST GASES
MULTIPLE-HEARTH INCINERATOR
ASH TO ULTIMATE DISPOSAL

b) Physical - chemical

Figure 1. Typical flowsheets for sludge treatment.

## Comparison Between Biological and Thermal Sludge Processing Systems

Biological processes have been used successfully to treat sludge for many years. The advantages of these processes are relatively simple operation, proven performance, and in the case of anaerobic digestion, the potential for energy recovery. On the other hand, they are subject to upsets caused by variations in the sludge and fluctuations in the biological flora and fauna in the reactor. For this reason, biological reactors are often not fully automated, requiring close monitoring by skilled operators. Finally, the end product of the biological stabilization process is a wet slurry which usually must be dewatered for economic disposal.

Thermal sludge processing systems, while quite complex in some cases, can be readily automated. The end product of thermal processing is a dry, sterile ash or char which is a small fraction of the total influent solids. The principal disadvantages to these systems are their relatively high capital cost, and the need for external fuel (oil or natural gas). The principal differences between biological and thermal sludge processing systems are summarized in Table 2.

## Thermal Processing of Sludge

There are only four types of thermal sludge processing systems commercially available. They include: multiple hearth furnaces, fluidized bed furnaces, electric furnaces, and single hearth cyclonic furnaces. Only the first two types of systems have been used extensively in the United States. There have also been many pyrolysis and gasification processes tested with sludge, but there are currently no such projects proposed or under development for sludge alone. All of the proposed projects in this category are designed for solid waste alone, or for the co-disposal of solid waste and sludge (41).

**Multiple Hearth Furnace** - The multiple hearth furnace (MHF) is the most widely used method of thermal sludge processing. In 1977 over 340 units were in operation in the United States (41). A typical MHF is shown in Figure 2. Dewatered sludge solids are admitted to the upper hearth and progressively transported to the lower hearths by the raking action of rotating rabble arms. Combustion air flow is counter to the sludge flow. Because temperatures often exceed 900°C, the rabble arms and central drive shaft are air cooled, and the outer shell of the furnace is refractory lined.

MHF's are designed for continuous operation. Because of the refractory lining, 24 to 30 hours are required to bring a cold furnace up to temperature or cool it. For this reason MHF's are usually not installed at small treatment plants, many of which are only manned eight hours per day.

In most MHF systems, auxiliary fuel is required to combust dewatered sludge solids. If sludge can be dewatered enough, autogenous combustion of the sludge can take place (i.e., self-sustaining combustion). The autogenous point can be estimated with the following equation:

$$P = \frac{W}{Q + W} \times 100\%$$

## Table 2

## CHARACTERISTICS OF BIOLOGICAL AND THERMAL SLUDGE PROCESSING SYSTEMS

| Parameter | Type of System | |
|---|---|---|
| | **Biological** | **Thermal** |
| Residence time | Long (3 to 60 days) | Short (10sec to 1 hour) |
| Start up time | Long (9 to 180 days) | Short (20min to 24 hours) |
| Operational temperature | Low (20 to 35°C) | High (300 to 1100°C) |
| Operational complexity | Moderate | Low to high |
| Potential for automation | Moderate | Very high |
| Preferred feedstock | Nutritionally balanced, wet slurry | Dry |
| Residue | Biologically active, wet slurry | Dry, sterile ash or char |

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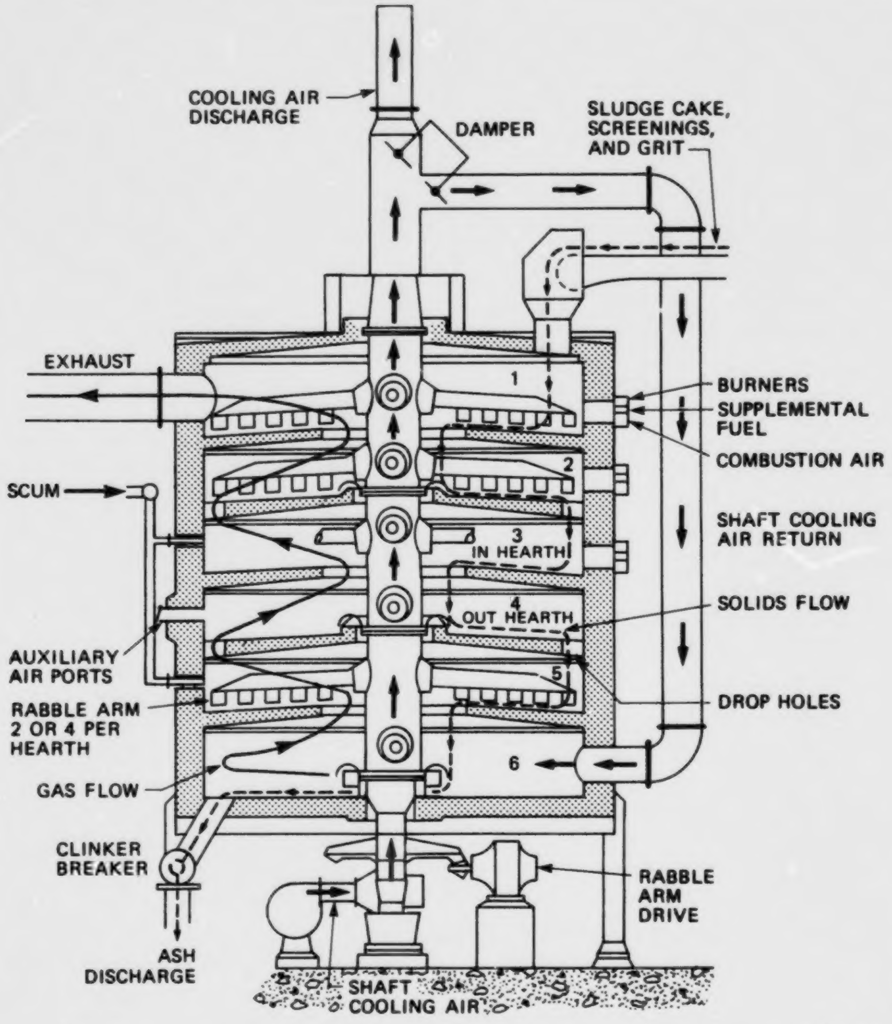
COOLING AIR DISCHARGE
DAMPER
SLUDGE CAKE, SCREENINGS, AND GRIT
EXHAUST
1
BURNERS
SUPPLEMENTAL FUEL
COMBUSTION AIR
2
SCUM
3
IN HEARTH
SHAFT COOLING AIR RETURN
4
OUT HEARTH
SOLIDS FLOW
AUXILIARY AIR PORTS
5
RABBLE ARM 2 OR 4 PER HEARTH
DROP HOLES
6
GAS FLOW
CLINKER BREAKER
RABBLE ARM DRIVE
ASH DISCHARGE
SHAFT COOLING AIR

**Figure 2.** **Cross section - multiple hearth sludge furnace. (After reference 41)**

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where:

P = Minimum percentage of solids in sludge for autogenous combustion
Q = Energy content of dry sludge, MJ/kg
W = Heat required to evaporate one kg of water in an MHF, MJ/kg

In an operating MHF the heat required to evaporate one kg of water is about 4.64 MJ/kg. However due to radiation losses and heating of the gas streams and sludge solids a value of about 8.12 MJ/kg is used (41). The energy content of the dry sludge solids, Q, is relatively high, typically about 18 MJ/kg. But this value is highly variable, dependent on wastewater characteristics, operation of the wastewater treatment plant, and the presence of chemicals such as lime or ferric chloride which are used to condition sludge for dewatering.

For many wastewater treatment plant sludges the autogenous point is in the range of 30 to 40 percent. However currently available sludge dewatering equipment cannot consistently produce a dewatered sludge cake in this range. Thus MHF's (and all other thermal sludge processing techniques) must have provisions for auxiliary fuel to account for these variations. This requirement for expensive and scarce auxiliary fuels such as natural gas or fuel oil has been the prime motivation for the development of co-disposal systems which use municipal solid waste as the auxiliary fuel.

Due to stringent carbonyl and unburned hydrocarbon emission limitations in many states, afterburning of MHF exhaust gases is usually required. This requires additional auxiliary fuel. In this respect multiple hearth furnaces are at a disadvantage compared to fluidized bed and single hearth cyclonic furnaces which do not require afterburning.

**Fluidized Bed Furnace** - The fluidized bed furnace (FBF) is the second most popular thermal processing system for sludge in the United States, with 60 units in operation (41). As shown in Figure 3, an FBF is a vertically oriented, refractory lined steel cylinder which contains a sand bed, a supporting grid plate, and air injection tuyeres. The sand bed is typically about 0.8 m thick. Air is forced through the bed at a pressure of 21 to 34 kPa gage, expanding the bed to twice its rest volume. Usually FBF's are operated with 20 to 45 percent excess air. This is less excess air than used with multiple hearth furnaces, so fluidized beds generally operate at higher heat efficiencies for a given exhaust temperature. Bed temperature is maintained between 760 to 820°C by auxiliary burners. The bed has a heat storage effect, allowing for rapid start-up after brief shut down periods (e.g., overnight).

Sludge is injected into the expanded bed at the bottom of the furnace. Turbulent mixing in the expanded bed results in good heat transfer between the sand grains, sludge, and hot combustion gases. The sand grains tend to have a comminuting effect on the ash, preventing the buildup of clinkers. However, finely ground ash is carried out of the furnace with the exhaust gases. Thus, air pollution control devices such as wet scrubbers, must be used to meet particulate emission limitations. A portion of the sand bed is also lost in the exhaust gases, about 5 percent of the bed volume for every 300 hours of operation.

Fluidized bed furnaces have a minimum of mechanical components and are relatively easy to operate. Most of the operating problems experienced with them

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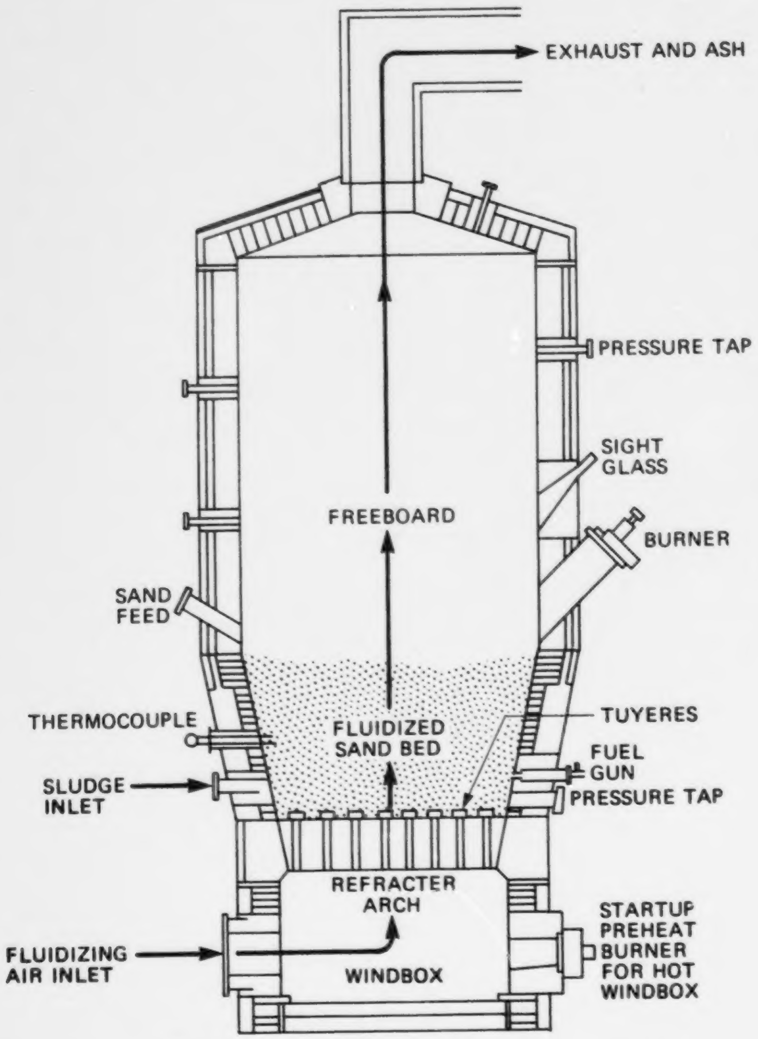
EXHAUST AND ASH
PRESSURE TAP
SIGHT GLASS
FREEBOARD
BURNER
SAND FEED
THERMOCOUPLE
FLUIDIZED SAND BED
TUYERES
FUEL GUN
SLUDGE INLET
PRESSURE TAP
REFRACTER ARCH
FLUIDIZING AIR INLET
WINDBOX
STARTUP PREHEAT BURNER FOR HOT WINDBOX

**Figure 3. Cross section - fluidized bed sludge furnace. (After reference 41)**

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have been with sludge feeding equipment and automatic temperature control systems. As with the multiple hearth furnace, auxiliary fuel is required.

**Electric Furnace** - The electric furnace (EF) is a relatively new concept in thermal sludge processing. The first unit was installed in the United States in 1975 (41). As shown in Figure 4, sludge enters through an airlock and is distributed evenly over a moving horizontal woven wire belt. Supplementary energy for non-autogenous sludge is provided by infrared heating elements. Because this energy is in the form of electricity, operating costs of an EF can be quite high. Also critical parts such as the woven wire belt and the infrared elements have been shown to have a short life (three to five years).

**Single Hearth Cyclonic Furnace** - Cyclonic furnaces were developed by the British and several units are in operation in Great Britain (41). As shown in Figure 5, the furnace consists of a vertical cylinder with a refractory lining. There is one rotating hearth and a fixed plow which moves sludge towards the center of the hearth where ash is collected. Combustion air and supplemental fuel are injected tangentially into the furnace. Cyclonic furnaces have a relatively low capital cost due to their mechanical simplicity. However maintenance problems have been experienced with the sludge feed mechanism.

## RESOURCE RECOVERY FROM SOLID WASTE

The need for supplemental fuel to thermally process sludge has been discussed. An alternative to fossil fuels might be the use of municipal solid waste. The physical characteristics of solid waste and how it can be processed into a fuel is reviewed below.

### Definition

Tchobanoglous, et al (52), have defined solid waste as:

> ". . . all the wastes arising from human and animal activities which are normally solid and that are discarded as useless or unwanted."

The Resource, Conservation, and Recovery Act of 1976 (45) defines solid wastes as:

> ". . . any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material . . . "

Note that the Resources, Conservation, and Recovery Act (RCRA) specifically defines sludge as a solid waste. This is an important legal consideration because RCRA clearly involves the solid waste manager with the sludge disposal problem and promotes the concept of co-disposal of sludge and solid waste in a common facility.

### Composition of Solid Waste

Solid waste has long been recognized as a misused resource. It contains valuable components that can be recovered and reused or combusted for their energy content. The most significant characteristics of municipal solid waste in the United States are

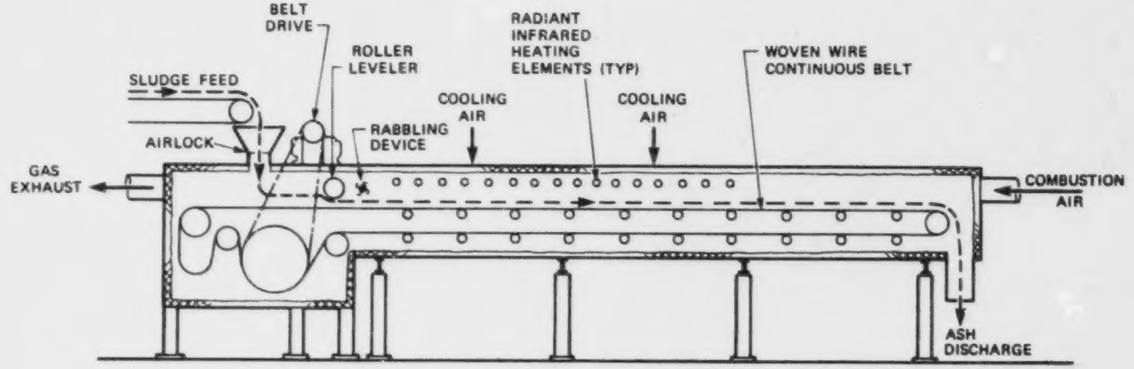
BELT DRIVE
ROLLER LEVELER
RADIANT INFRARED HEATING ELEMENTS (TYP)
WOVEN WIRE CONTINUOUS BELT
SLUDGE FEED
COOLING AIR
COOLING AIR
AIRLOCK
RABBLING DEVICE
GAS EXHAUST
COMBUSTION AIR
ASH DISCHARGE

Figure 4. Cross section - electric sludge furnace.
(After reference 41)

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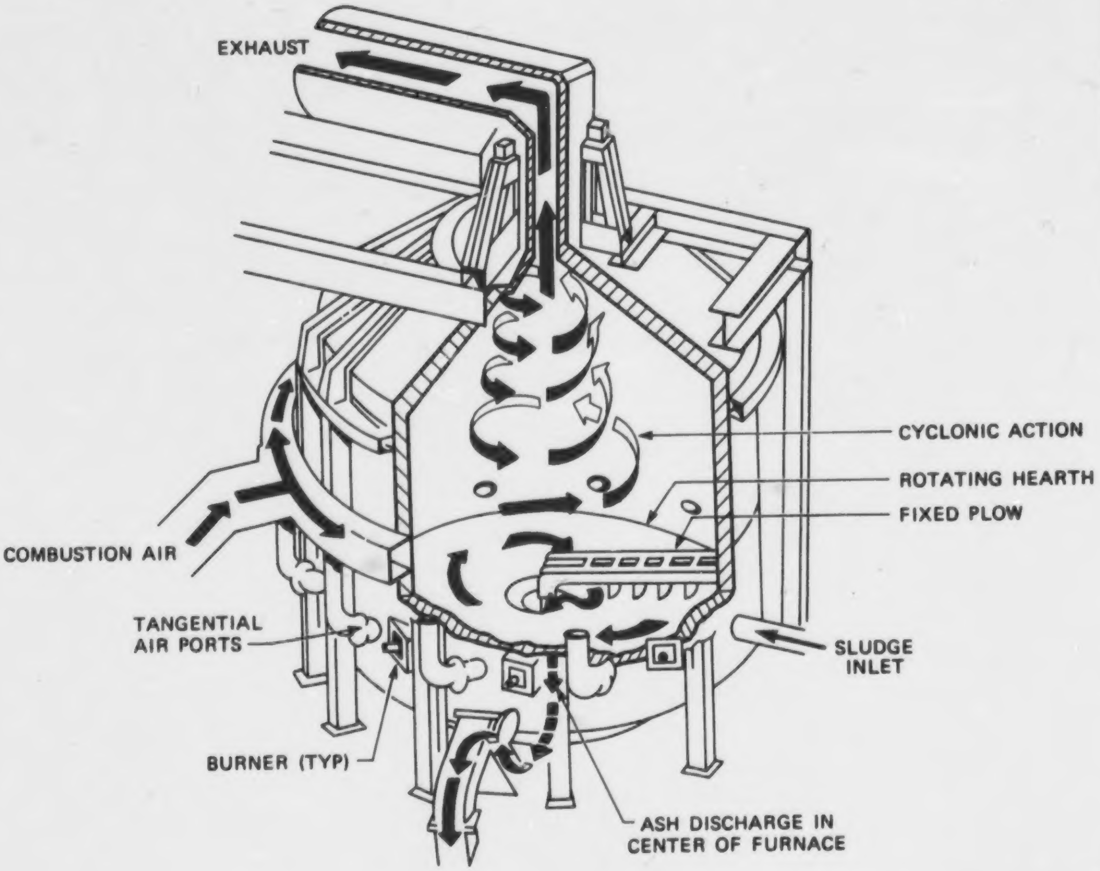
EXHAUST
CYCLONIC ACTION
ROTATING HEARTH
FIXED PLOW
COMBUSTION AIR
TANGENTIAL AIR PORTS
SLUDGE INLET
BURNER (TYP)
ASH DISCHARGE IN CENTER OF FURNACE

**Figure 5. Cross section - cyclonic sludge furnace. (After reference 41)**

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summarized in Table 3. The percent by weight, moisture content, and energy content of each component are given. Note that although municipal solid waste has an overall energy content of only 10.5 MJ/kg at 20 percent moisture content, paper, which typically makes up 40 percent of U.S. solid waste, has a much higher energy content of 16.7 MJ/kg at a low moisture content of six percent.

## Mixed Waste Recovery Systems

Mixed waste recovery is the mechanical separation of solid waste into its various components. The primary function of mixed waste recovery is to produce a combustible refuse derived fuel (RDF) which can be either burned on site for electricity or steam production or sold to an adjacent government or industrial customer.

RDF is produced by a process train which separates solid waste into a combustible light fraction consisting primarily of paper, plastics, and food wastes; and a non-combustible heavy fraction containing metals, glass, and ash and dirt. A typical process flowsheet for producing shredded RDF is shown in Figure 6.

Although the recovered materials have considerable value (e.g., ferrous scrap $22/metric ton, aluminum $550/metric ton, clean glass cullet $22/metric ton), RDF is the principal source of revenue for a mixed waste recovery system. At $17 to $40/metric ton, RDF can represent 85 to 95 percent of project revenues (44). Several large scale RDF systems have been economic failures because they either produced a low quality RDF which the customer would not accept (Milwaukee, Wisconsin), or they could not find a market at all for the RDF (New Orleans, Louisiana) (46).

Based on the limited operating experience which exists in the United States with RDF systems, the following minimum criteria have been proposed for future projects (46):

"1. Large scale resource recovery can only be economical in large metropolitan areas where landfill sites are unavailable or very expensive, above $25/metric ton.

2. There must be an adequate refuse supply committed to the facility (a minimum of 1800 metric tons/day is required).

3. A customer must be obtained for the steam or power generated by the plant and must be located close by. Firm contracts must be obtained for both the refuse and the sale of energy.

4. If the customer is to be an industrial facility, it may be necessary to design the facility with the capability of burning fossil fuel when refuse is unavailable or when the plant cannot process the raw refuse due to malfunctions of the processing equipment.

5. The logistics of delivering refuse to the resource recovery facility should be planned long in advance."

These guidelines reflect the prevailing engineering philosophy towards RDF systems which favors very large systems. Based on an average U.S. municipal solid

## Table 3

## [a]COMPOSITION, MOISTURE, AND ENERGY CONTENT OF SOLID WASTE

| Component | Percent by weight |  | Moisture, Percent |  | Energy[b], MJ/kg |  |
|---|---|---|---|---|---|---|
|  | Range | Typical | Range | Typical | Range | Typical |
| Food wastes | 6 - 26 | 15 | 50 - 80 | 70 | 3.5 - 7.0 | 4.7 |
| Paper | 25 - 45 | 40 | 4 - 10 | 6 | 11.6 - 18.6 | 16.7 |
| Cardboard | 3 - 15 | 4 | 4 - 8 | 5 | 14.0 - 17.4 | 16.3 |
| Plastics | 2 - 8 | 3 | 1 - 4 | 2 | 27.9 - 37.2 | 32.6 |
| Textiles | 0 - 4 | 2 | 6 - 15 | 10 | 15.1 - 18.6 | 17.4 |
| Rubber | 0 - 2 | 0.5 | 1 - 4 | 2 | 20.9 - 27.9 | 23.3 |
| Leather | 0 - 2 | 0.5 | 8 - 12 | 10 | 15.1 - 19.8 | 17.4 |
| Garden trimmings | 0 - 20 | 12 | 30 - 80 | 60 | 2.3 - 18.6 | 6.5 |
| Wood | 1 - 4 | 2 | 15 - 40 | 20 | 17.4 - 19.8 | 18.6 |
| Glass | 4 - 16 | 8 | 1 - 4 | 2 | 0.1 - 0.2 | 0.1 |
| Tin cans | 2 - 8 | 6 | 2 - 4 | 3 | 0.2 - 1.2 | 0.7 |
| Nonferrous metals | 0 - 1 | 1 | 2 - 4 | 2 | - | - |
| Ferrous metals | 1 - 4 | 2 | 2 - 6 | 3 | 0.2 - 1.2 | 0.7 |
| Dirt, ashes, brick, etc. | 0 - 10 | 4 | 6 - 12 | 8 | 2.3 - 11.6 | 7.0 |
| Overall value | - | - | 15 - 40 | 20 | 9.3 - 12.8 | 10.5 |

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[a] After Reference 52

[b] As discarded basis, HHV

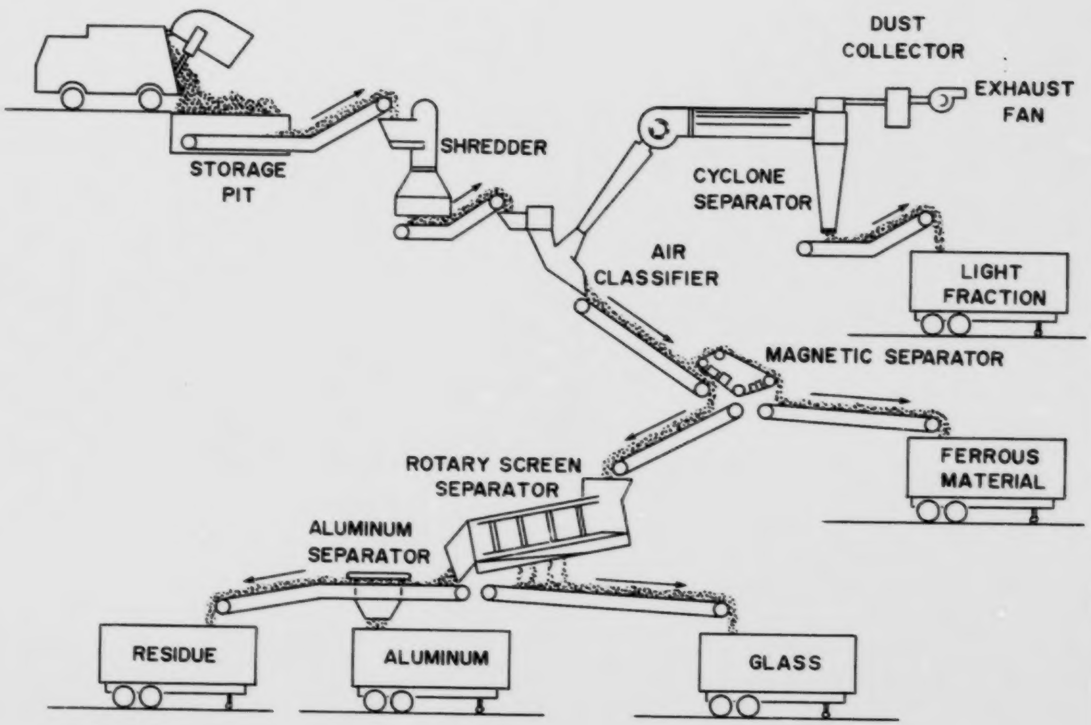
DUST
COLLECTOR
EXHAUST
FAN
SHREDDER
STORAGE
PIT
CYCLONE
SEPARATOR
AIR
CLASSIFIER
LIGHT
FRACTION
MAGNETIC SEPARATOR
FERROUS
MATERIAL
ROTARY SCREEN
SEPARATOR
ALUMINUM
SEPARATOR
RESIDUE
ALUMINUM
GLASS

Figure 6. Typical mixed waste recovery system.
(After reference 52)

waste generation rate of 1.59 kg/cap•day, the recommended minimum size of 1800 metric tons/day of refuse mentioned in item 2 represents a service population of 1.13 million persons. The smallest RDF system in the United States, at Ames, Iowa, is only a tenth of this size, processing 180 metric tons/day. But the Ames plant operates with a heavy city subsidy.

## Densified Refuse Derived Fuel

Densified refuse derived fuel (d-RDF) is an alternative to conventional shredded RDF. It is produced by compressing RDF into dense pellets or cubes. The primary advantage of d-RDF is that it is storable and easy to transport in comparison to conventional RDF which must be burned at the production site. An additional advantage is that d-RDF can be burned in small stoker type boilers. These boilers, in the 11,000 to 90,000 kg steam/hr range, are too small to be converted economically to run on shredded RDF. However d-RDF can often be directly subsituted for coal in these boilers (58).

One of the first d-RDF systems in the United States was operated during the early 1970's by the City of Ft. Wayne, Indiana, to produce fuel for the municipal power plant. A John Deere stationary alfalfa cuber was used to densify the light fraction of municipal and industrial solid waste from a mixed waste recovery system. The cubes were burned on a 1:3 ratio with coal in a 40,000 kW steam electric power plant (21). A commercially produced solid waste densification system using a modified John Deere cuber is currently being marketed by the Papakube Corporation of San Diego, California (37,38).

## Source Separation of Solid Waste

Source separation is an alternative resource recovery technique for small communities. It can replace the high technology, capital intensive mixed waste recovery systems previously discussed. Most source separation systems are operated for materials recovery, not energy recovery. Thus their financial success is dependent on the highly fluctuating secondary materials market.

In source separation systems, residents are requested to place bundles of newspaper and containers with aluminum and steel cans out with their weekly trash collection. The newspaper and other recyclables are picked up by the regular collectors and carried in special containers or racks on the trash trucks. In other cities a smaller separate vehicle is used to collect paper and other recyclable materials. Usually, cities require that newspaper be tied into bundles. Magazines, paper bags, and food packaging are not accepted. Such a system is currently operated by the City of Davis, California (see Figure 7).

It has been assumed for the past few years that the recycling of waste paper into newsprint or low quality paper is both economically and ecologically sound. However, current energy prices, coupled with the fluctuating nature of newsprint prices, are making energy recovery a viable option. Also, because only prime, hand selected clean newsprint is suitable for recycling purposes, far more waste paper is available for energy recovery as cleanliness is not as critical.

A source separation system designed to recover waste paper for use as a fuel could be less restrictive. As a result, a higher proportion of a given community's

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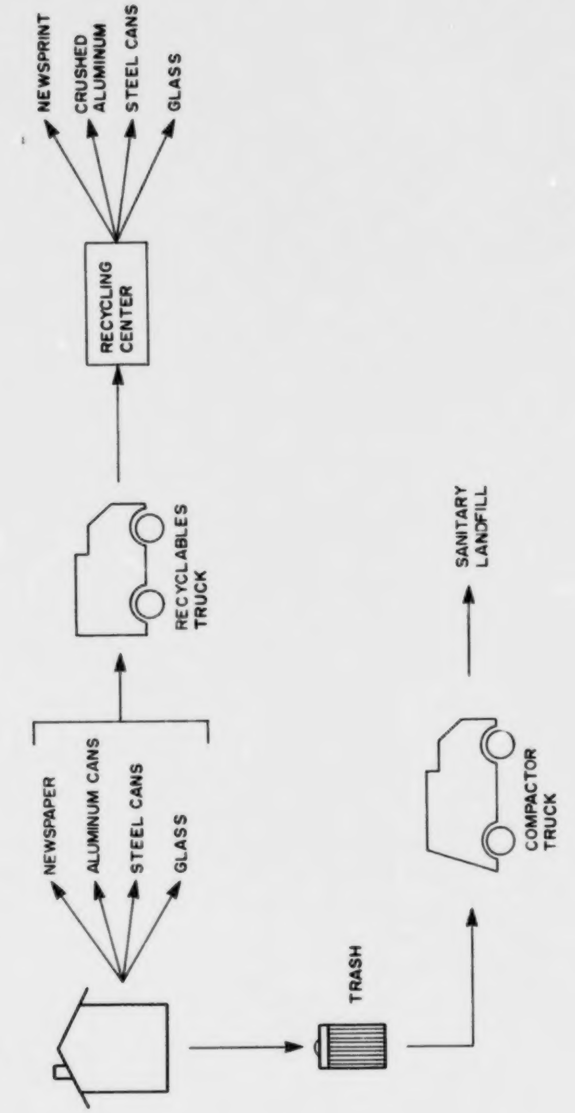
NEWSPAPER
ALUMINUM CANS
STEEL CANS
GLASS
RECYCLABLES TRUCK
RECYCLING CENTER
NEWSPRINT
CRUSHED ALUMINUM
STEEL CANS
GLASS
TRASH
COMPACTOR TRUCK
SANITARY LANDFILL

Figure 7. Materials recovery from source separated solid waste.

waste paper could be recovered. Such a system is shown in Figure 8. In this system, only a combustible fuel fraction is recovered. No attempt is made to recover steel cans and glass because marketing of these components is difficult and seldom economic for small communities. Aluminum, because of its high value could also be recovered.

## ENERGY RECOVERY FROM SOLID WASTE

Energy can be recovered from municipal solid waste (MSW) in the form of steam or electricity. There are two basic methods of approach: the mass burning of unseparated solid waste, and the combustion of refuse derived fuel. The relative merits of each approach are discussed below.

### Mass Burning - Water Wall Incinerators

Mass burning of solid waste in a water wall incinerator is the most widely used method of energy recovery. Eight units are being operated in the United States while over 200 units are in use in Europe (54).

In a water wall incinerator, unseparated solid waste is fired on stoker grates similar to those used in coal fired boilers. Energy recovery is accomplished by passing hot combustion gases over water filled heat exchanger tubes for the generation of steam. Because solid waste is unseparated prior to firing, metal, glass, and other uncombustible materials are passed through the incinerator into the ashpit. These materials become fused together into a slag-like mass which must be landfilled. Thus the metal and glass originally in the waste are not recoverable. Metal in the waste also tends to fuse on grate mechanisms, and ash handling equipment, requiring expensive maintenance. A capacity of about 180 metric tons/day is considered to be the minimum practical size by most manufacturers.

### Mass Burning - Modular Incinerators

Modular incinerators are batch fed, package units without continuous ash removal. Originally designed for solid waste reduction only, recent units have incorporated waste heat boilers for energy recovery. Twelve systems are in operation or under construction in the United States, ranging in capacity from 15 to 218 metric tons/day (54).

They consist of a refractory lined cylinder containing a fixed grate. Unseparated solid waste is loaded into the incinerator with a front end loader or similar equipment. Two stage combustion is used in most units, with sub-stoichiometric air used in the main combustion chamber, and excess air used in an afterburner section. After completion of the combustion cycle, the unit is opened, and the ash removed manually.

Modular incinerators are factory built and highway shipable. Clusters of units can be used to increase capacity. Operational problems have included poor combustion performance, slagging of metals and glass, and deterioration of refractory liners. The metal and glass in the ash are essentially non-recoverable.

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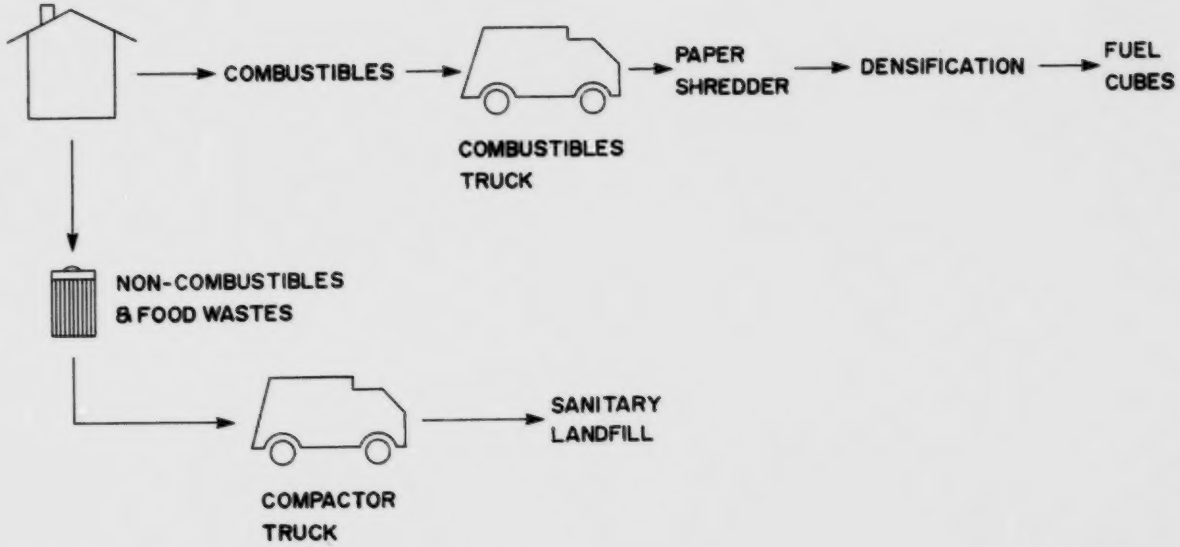
COMBUSTIBLES
COMBUSTIBLES TRUCK
PAPER SHREDDER
DENSIFICATION
FUEL CUBES
NON-COMBUSTIBLES & FOOD WASTES
COMPACTOR TRUCK
SANITARY LANDFILL

Figure 8. Production of densified refuse derived fuel from source separated solid waste.

## Combustion of RDF

The combustion of refuse derived fuel (RDF) can reduce or eliminate many of the problems encountered in mass firing of solid waste. Because the waste is separated prior to combustion, recovery of aluminum, ferrous metals, and glass can be accomplished. Removal of these materials also reduces the potential for slagging and other maintenance problems which occur with the mass firing of unseparated solid wastes.

Shredded RDF can be burned in suspension fired boilers at considerably higher efficiencies than experienced with mass fired systems. Densified RDF can be burned in conventional stoker fed coal boilers. The ability of standard boilers and steam power plants to use shredded or densified RDF as a supplementary fuel is the greatest advantatge of RDF combustion over the mass firing approach which requires a dedicated solid waste combustion facility.

The principal disadvantages to RDF combustion include: high capital and operating costs of RDF facilities, fluctuating quality of RDF which can adversely affect combustion efficiency, and materials handling problems during RDF production. Operational experience with RDF combustion is limited to five years operation with shredded RDF at the Ames, Iowa, plant; a one year test with d-RDF at the Ft. Wayne, Indiana, power plant; and one year test with d-RDF at the Union Electric power plant in St. Louis, Missouri. Eight full scale RDF combustion systems are currently in the design, construction, or start up stages in the United States (16,44, and 54).

# CO-DISPOSAL OF SLUDGE AND SOLID WASTE

The main disadvantage to the thermal processing of sewage sludge is the need for auxiliary fossil fuel. Co-disposal of sludge and solid waste in a common system would eliminate or reduce the need for fossil fuels for the incineration of sludge, while reducing the landfill requirements for solid waste. Currently available technology for co-disposal, and several innovative co-disposal processes currently under development are considered in the following discussion.

## Review of Co-disposal Processes

Currently, there are no full scale co-disposal systems operating in the United States, however, several facilities are under construction or in the design stage. These projects are summarized in Table 4. Co-disposal processes are of two basic types: in the first type, a mass fired solid waste incinerator is used to combust dried sludge which has been mixed with unseparated municipal solid waste; in the second type, a sewage sludge incinerator is modified to accept refuse derived fuel (RDF) as a substitute for the natural gas or oil normally used in such furnaces.

Experience with full scale co-disposal systems has shown that external drying or dewatering of sludge is required for the successful combustion of sludge in mass fired incinerators (48). Although direct injection of liquid sludge into incinerators has been attempted in the past, it has failed in every application, probably due to poor mixing between the sludge and solid waste in the incinerator, and the tendency for the liquid sludge to form crusts on the stokers in the incinerator (48). All of

## Table 4

## PLANNED CO-DISPOSAL FACILITIES IN THE UNITED STATES[a]

| Location | Type | Description | Status[b] |
|---|---|---|---|
| Contra Costa County, California | Sludge incinerator utilizing RDF | Envirotech multiple hearth furnace operated in the gasification mode. Energy recovery by steam turbine. | Facility plan completed |
| Duluth, Minnesota | Sludge incinerator utilizing RDF | Fluidized bed sludge incinerator. Energy recovery by steam turbine. | Under construction |
| Glen Cove, New York | Mass fired solid waste incinerator | Stoker grate furnace using mixed solid waste and dewatered sludge. Energy recovery by steam turbine. | Under EPA review |
| Harrisburg, Pennsylvania | Mass fired solid waste incinerator | Existing mass fired incinerator modified for sludge disposal. | Under construction |
| Memphis, Tennessee | Sludge incinerator utilizing RDF | Multiple hearth furnace operated in the gasification mode. Heat recovery boiler with sale of steam. | Under EPA review |

[a] Adapted from Reference 16

[b] Status as of September 1979

the proposed mass fired co-disposal systems discussed in Table 4 employ external sludge drying or dewatering.

Modification of existing multiple hearth or fluidized bed sludge incinerators to utilize RDF has proven successful in pilot testing. The Central Contra Costa County, California AWT wastewater plant will utilize a modified multiple hearth furnace operating in the gasification mode with RDF as the auxiliary fuel (16).

### PTGL Processes for Co-disposal

There are many pyrolysis, thermal gasification, and liquifaction (PTGL) processes being proposed for the conversion of biomass, sludge, and municipal, industrial, and agricultural waste into solid, gaseous, and liquid fuels. An excellent overview of many of the processes currently under development is given in Reference 27. Two of the processes most often mentioned in connection with sludge disposal are the Purox vertical shaft gasifier and the Envirotech multiple hearth gasifier.

**The PUROX Vertical Shaft Gasifier** - Although often referred to as a pyrolysis process in the literature, the PUROX reactor is actually a vertical fixed bed, counter-current flow gasifier. Pure oxygen is used as an oxidant and the output consists of a medium energy gas ($\approx$13 MJ/$m^3$) and a molten slag. After scrubbing, the gas can be combusted in a heat recovery boiler. In a large scale test conducted at the Charleston, West Virginia PUROX pilot plant, successful operation of the PUROX reactor in the co-disposal mode was demonstrated. Test runs were made with mixed municipal solid waste and dewatered raw primary sludge, and dewatered mixed biological and primary sludges (35). In spite of this highly successful demonstration project, there are currently no PUROX co-disposal systems in the planning or funding stages (16).

**The Envirotech Multiple Hearth Gasifier** - In 1976, the Envirotech Corporation in conjunction with Brown and Caldwell Consulting Engineers, demonstrated the operation of a multiple hearth sludge furnace using RDF as an auxiliary fuel (4). The furnace was operated both in its original configuration as an incinerator and in the pyrolysis mode. In actuality, the furnace was operated as a counter-current flow, air blown gasifier. The multiple hearth gasifier produced a low energy gas (5.2-6.0 MJ/$m^3$) which was combusted in an afterburner during the tests. Based on these highly successful experiments, a full scale multiple hearth gasifier is in the final design stages for the Contra Costa County, California and a similar facility is proposed for Memphis, Tennessee (see Table 4).

## GASIFICATION AS A CO-DISPOSAL OPTION

The refuse derived fuel systems, energy recovery units, and co-disposal processes reviewed in the previous sections are designed for large communities on the order of at least 100,000 population. However the ever increasing costs of energy and sludge and solid waste disposal make small scale co-disposal attractive.

An alternate system for sludge disposal that could be used by small communities: the co-gasification of sludge and source separated solid waste is considered in this section. Such a system is shown schematically in Figure 9. The system consists of the following components: a shredder to reduce the size of the waste paper and mix it with dewatered sludge, a densification system to convert the sludge/waste paper

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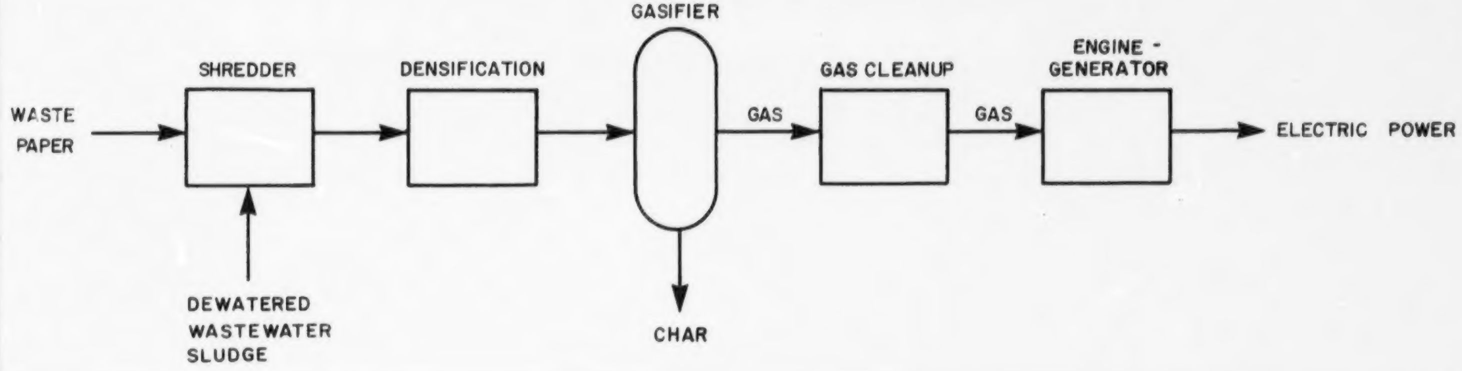
WASTE PAPER
SHREDDER
DEWATERED WASTEWATER SLUDGE
DENSIFICATION
GASIFIER
CHAR
GAS
GAS CLEANUP
GAS
ENGINE - GENERATOR
ELECTRIC POWER

Figure 9. Gasification system for sludge and source separated solid waste.

mixture into a dense fuel cube, the gasification reactor, a gas cleanup system, and an engine-generator set to convert the gas to electrical energy.

## Gasification of Sludge/Solid Waste Mixtures

Downdraft gasifiers are simple to construct and operate but they have exacting fuel requirements which include:

1. moisture content < 20 percent
2. ash content < 6 percent
3. uniform particle size with good mechanical stability

Because waste can be dried prior to gasification, excessive moisture can be overcome. However, ash content and particle size are more difficult to handle. When the ash content is higher than 6 percent, there is a sufficient amount of ash to melt and solidify into slag which can cause severe operational problems. Excessive fine material in the fuel can cause mechanical bridging in the fuel hopper. One method of overcoming these problems is to use more complex reactors such as the Envirotech Multiple Hearth System or high temperature slagging gasifiers, such as the PUROX process, in which the ash is melted. Although both of these approaches are operationally feasible, they are costly and complex.

A lower cost approach is to utilize the simplest reactor type, the downdraft gasifier, and tailor the fuel accordingly. A suitable fuel can be made by mixing dewatered sludge with the paper fraction of source separated solid waste, and densifying the mixture to produce a densified refuse derived fuel (d-RDF) that has low moisture content, low ash content, and uniform particle size. The details of this operation are discussed in a later chapter.

## An Integrated Waste Management System for Small Communities

Although a gasification system could be operated in a small community strictly with source separated solid waste and sludge, a more cost effective approach might be to incorporate the gasification system with the other waste generating activities of the city and its environs. An example of such a system is shown in Figure 10. If the gasifier system is located at the site of the city wastewater treatment plant, the low energy gas produced could be used efficiently on-site to power pumps, blowers and other equipment.

Provisions could also be made for the inclusion of urban biomass. Operation of downdraft gasifiers with a wide range of agricultural wastes has already been demonstrated in previous gasification research conducted at the University of California, Davis (26,59,60, and 61). In rural areas, agricultural wastes could be obtained at little or no cost during some seasons. However, these wastes would still require collection and densification prior to use. These supplemental biomass fuels would increase the utilization of the system.

## Use of Urban Biomass As a Fuel Source

Urban biomass can be defined as organic materials that are generated in an urban environment as a by-product of landscaping and other horticultural activities.

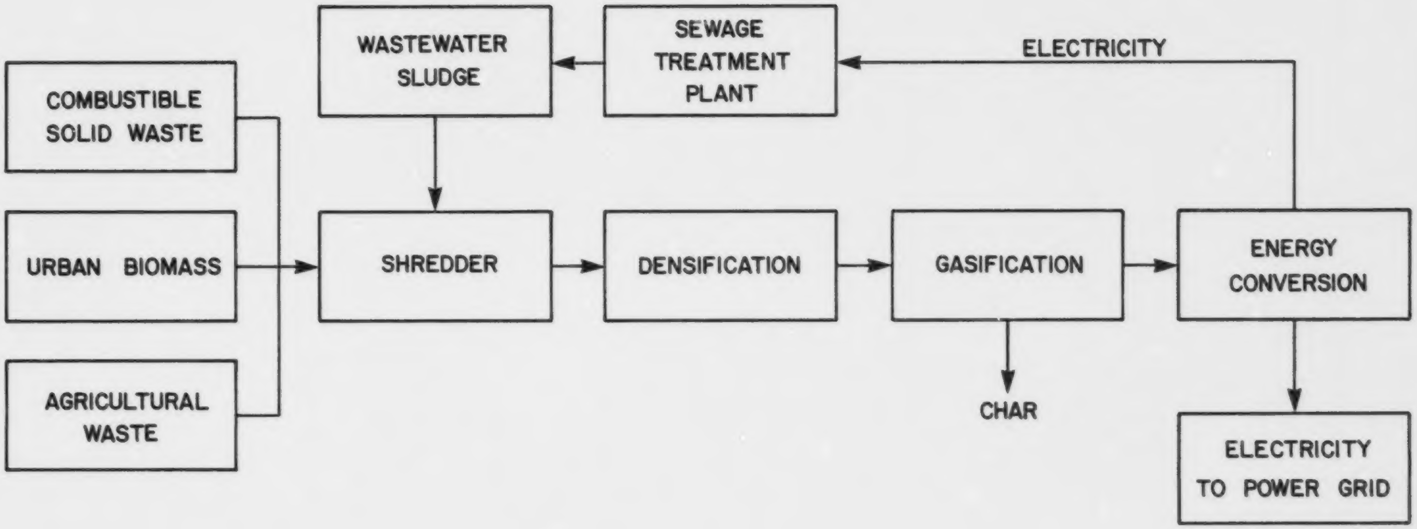
COMBUSTIBLE SOLID WASTE
URBAN BIOMASS
AGRICULTURAL WASTE
WASTEWATER SLUDGE
SEWAGE TREATMENT PLANT
ELECTRICITY
SHREDDER
DENSIFICATION
GASIFICATION
ENERGY CONVERSION
CHAR
ELECTRICITY TO POWER GRID

Figure 10. An integrated gasification system for co-disposal of various wastes.

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It is composed of tree trimmings, grass clippings, and other yard wastes. In many communities this material is already collected in separately. The amounts collected can be quite substantial. For example in Davis, California, a largely residential community of 32,000 persons, in 1979, the urban biomass collected ranged for 213 metric tons in January to 263 metric tons in December (wet basis).

## Preparation of Biomass Fuel

The use of biomass as a fuel source would probably require that it be dried, shredded, and densified prior to use. The shredded and dried material could be blended with waste paper and sludge in an integrated waste management system. Drying could be accomplished with waste heat from the gasifier system, with solar energy by spreading the biomass on a hard surface, or with forced, ambient air drying in a large bin.

## Utilization of Low Energy Gas

The low energy gas from a downdraft gasifier can be utilized in several ways. The simplest technique is to burn the gas in a standard boiler designed for natural gas. This requires a low energy gas burner designed for the greater gas and combustion air volumes, and a larger gas feed line to account for the lower energy content of the gas (≈ 5.6 MJ/m$^3$) as compared to natural gas (≈ 37.3 MJ/m$^3$).

Another approach is to cool and filter the gas and utilize it as an alternative fuel for spark and compression ignition engines (24,47, and 60). Skov and Papworth (47) described the operation of gasoline engine powered trucks, buses, and agricultural equipment in Europe with gas produced using portable wood, charcoal, coal, and fueled gasifiers. Gasifiers can also be used to fuel air heating burners. The amount of gas clean-up is dependent on the use for the heated air.

In an integrated gasification system for small communities the low energy gas could be burned in a stationary dual-fueled diesel engine-generator set. Two modes of operation are possible. In the first case the gasifier-engine-generator set is located at the fuel preparation site (the city wastewater treatment plant). Electricity produced in excess of local requirements would be fed into the local power grid. In the second case, fuel cubes could be produced at a central location and transported to satellite gasifier systems in other locations.

## GASIFICATION AS A UNIT OPERATION

Gasification is an energy efficient technique for reducing the volume of solid waste and the recovery of energy. Essentially, the process involves partial combustion of a carbonaceous fuel to generate a combustible fuel gas rich in carbon monoxide, hydrogen, and some saturated hydrocarbon gaes, principally methane. The historical development, the basic theory of operation, and the types of reactors used in the gasification process are discussed briefly below.

### Definition

Gasification involves the partial combustion of a carbonaceous fuel to generate a combustible gas containing carbon monoxide, hydrogen, and gaseous hydrocarbons.

Currently, there is much confusion in the literature between the terms "pyrolysis" and "gasification." In this thesis, the following definitions given by Lewis (29) are used.

> "Pyrolysis - Thermal processing of waste in the absence of oxygen, in (a) indirectly heated retorts, and (b) furnaces that are directly heated by fuel gases from a burner firing on a stoichiometric air/fuel ratio."
>
> "Gasification - Thermal processing of waste where a fraction of the stoichiometric oxygen required by the waste is admitted directly into the fuel bed to liberate the heat required for endothermic gasification reactions. The volatile portion of incoming waste will be pyrolyzed by the heat of the fuel gases, and the outlet gas composition will reflect both processes."

## Historical Development

Gasifers have been used since the 19th century. The first coal gasifiers were built by Bischof in Germany, 1839, Ebelman in France, 1840, and Ekman in Sweden, 1845. This was followed by the Siemens brothers in Germany, 1861. The Siemens' gasifiers were used primarily to fuel heavy industrial furnaces. The development of gas cooling and cleaning equipment by Dowson in England, 1881, extended the use of gasifiers to small furnaces and gas engines (42).

By the early 1900's, gasifier technology had advanced to the point where most ligno cellulosic materials such as wood, fruit pits, straw, and walnut shells could be gasified. These early gasifiers were used primarily to provide the fuel for stationary gasoline engines. Portable gasifiers also emerged in the early 1900's. They were used for ships, automobiles, trucks, and tractors. The real impetus for the development of portable gasifier technology was World War II. During the war years, France had over 60,000 charcoal burning cars while Sweden had about 75,000 wood burning gasifier equipped buses, cars, tractors, and engine powered boats. With the return of relatively cheap and plentiful gasoline and diesel oil, after the end of World War II, gasifier technology was all but forgotten. However, in Sweden, research has continued into the use of wood fueled gasifiers for diesel tractors and transport trucks. (39). Furthermore the downdraft gasification of peat is being pursued actively in Finland (24).

Although there has been considerable success reported with the gasification of charcoal, coal, wood, and certain agricultural wastes (9,17,32,49,59,60, and 61), the gasification of solid waste has not been as successful. It was stated in a recent editorial in a leading solid waste trade magazine that (46):

> "Pyrolysis [i.e., gasification] systems such as the Union Carbide Purox System, the Landguard System, and the Occidental Flash Pyrolysis System have been noble experiments, but are considered to be technical and economic failures."

It is felt that the principal causes for the failure of gasification technology in the solid waste field has been the complexity of the systems, and a lack of appreciation of the heterogeneous nature of solid waste, mixed with air dried sludge. The approach taken in this research, was to use as simple a reactor as possible, the vertical fixed bed gasifier and fuel it with source separated paper, the cleanest form of solid waste. The reader is referred to References 27 and 28 for an in-depth review of current research into pyrolysis and gasification systems.

## Reactor Types

Four basic types of reactors are used in gasification. They are:

1. vertical packed bed
2. multiple hearth
3. rotary kiln
4. fluidized bed

Most of the early gasification work in Europe was with the air-blown fixed bed type reactors. The other types are favored in current United States practice, with the exception of the PUROX oxygen blown gasifier (an updraft reactor).

The vertical, fixed bed, downdraft type reactor has a number of advantages over the other types including simplicity and relatively low capital cost. However, it is more sensitive to the mechanical characteristics of the fuel. The merits and limitations of vertical bed gasifiers are discussed in detail in Reference 12. Fuel flow is by gravity with air and fuel moving co-currently through the reactor (see Figure 11). At steady state, four zones form in the reactor. In the hearth zone, where air is injected radially into the reactor, partial combustion reactions predominate. Some heat transfers from this zone upward into the fuel mass, causing pyrolysis reactions in the distillation zone and partial drying of the fuel in the drying zone. Actual production of the fuel gas occurs in the reduction zone, which is below the partial combustion zone and where endothermic reactions predominate, forming CO and $H_2$. The hut carbon bed in the combustion zone and upper part of the reduction zone cracks much of the volatile hydrocarbons produced into methane and a small amount of other saturated and unsaturated hydrocarbon gases. The end products of the process are a carbon rich char and the low energy gas.

## Gasification Theory

A gasifier is basically an incinerator operating under reducing conditions. During the gasification process, five principal reactions occur:

| | | | |
|---|---|---|---|
| $C + O_2$ | = | $CO_2 + 393.8$ MJ/kg-mol | exothermic |
| $C + H_2O$ | = | $CO + H_2 - 131.4$ MJ/kg-mol | endothermic |
| $C + CO_2$ | = | $2CO - 172.6$ MJ/kg-mol | endothermic |
| $C + 2H_2$ | = | $CH_4 + 75.0$ MJ/kg-mol | exothermic |
| $CO + H_2O$ | = | $CO_2 + H_2 + 41.2$ MJ/kg-mol | exothermic |

The heats of reaction shown above are evaluated at 25°C and 1 atmosphere pressure. The heat to sustain the process is derived from the exothermic reactions while the combustible components of the low energy gas are primarily generated by the endothermic reactions. Although the reaction kinetics of the gasification process are quite complex and still the subject of considerable debate, the operation of air-blown, downdraft gasifiers of the type used in this research is straightforward. For a further discussion of gasification theory and reaction kinetics the reader is directed to References 18, 20, 42, and 49.

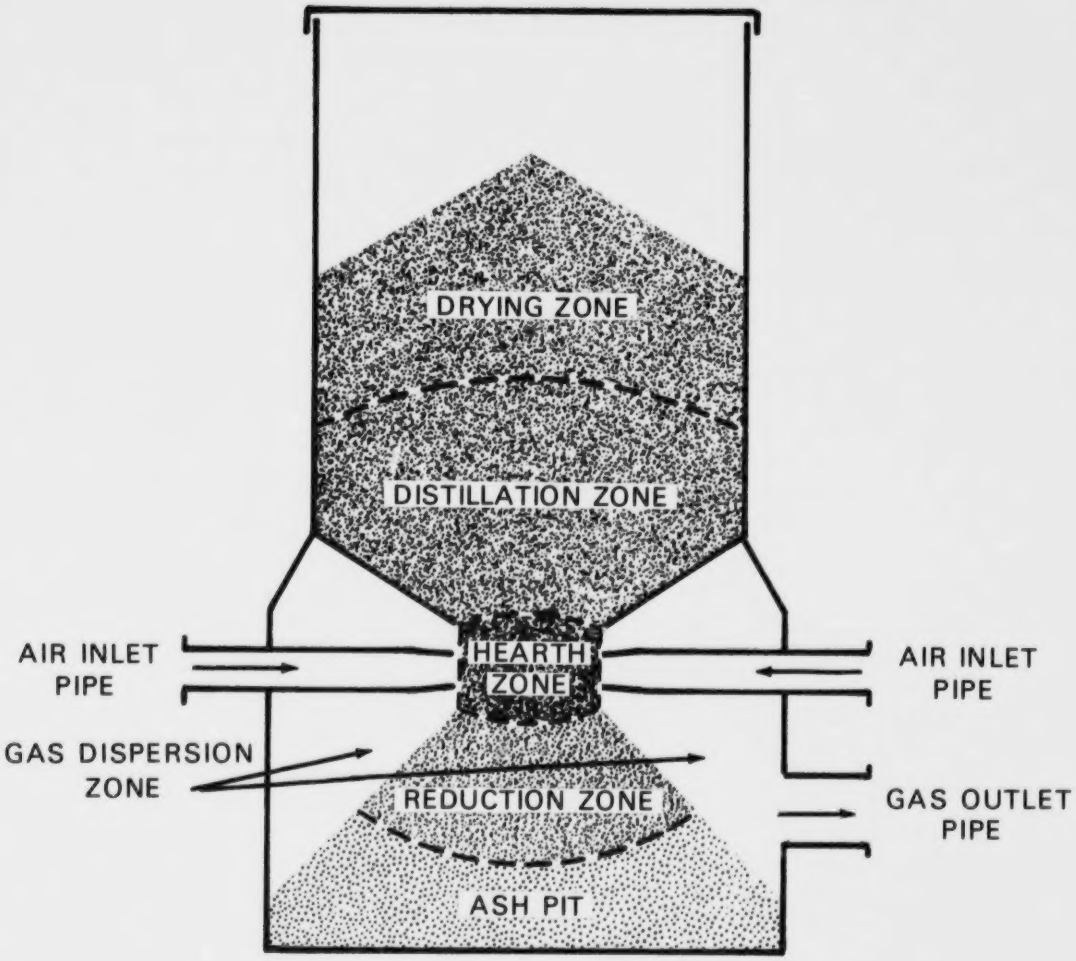
DRYING ZONE
DISTILLATION ZONE
AIR INLET PIPE
HEARTH ZONE
AIR INLET PIPE
GAS DISPERSION ZONE
REDUCTION ZONE
GAS OUTLET PIPE
ASH PIT

Figure 11. Schematic of a downdraft gasifier.

**Gas Composition**

When a gasifier is operated at atmospheric pressure with air as the oxidant, the end products of the gasification process are a low energy gas (LEG) typically containing (by volume) 10% $CO_2$, 20% CO, 15% $H_2$, 2% $CH_4$ with balance being $N_2$, and a carbon rich char. Due to the diluting effect of the nitrogen in the input air, the LEG has a energy content in the range of the 5.2 to 6.0 $MJ/m^3$. When pure oxygen is used as the oxidant, a medium energy (MEG), with an energy content in the range of 12.9 to 13.8 $MJ/m^3$, is produced (15). Because of their complexity and high capital cost, oxygen blown gasifiers have not been applied commercially (16). The simpler air blown gasifer has been used widely and is the subject of this research.

## SUMMARY

The co-disposal of sludge and solid waste is a promising solution to an environmental problem facing many communities. However current co-disposal technology is not affordable by smaller communities. The co-gasification of densified sludge and source separated solid waste in a simple fixed bed air-blown gasifier may be a new co-disposal technique that is appropriate for use by small communities.

# CHAPTER III

# EXPERIMENTAL APPARATUS, METHODS, AND PROCEDURES

The experimental work described in this report was conducted on the University of California, Davis campus using the facilities, shops, and laboratories of the Departments of Civil and Agricultural Engineering. The experimental gasification system, the preparation of densified fuels, and the methods and procedures used in the collection and analysis of the data are described in this chapter.

## EXPERIMENTAL GASIFICATION SYSTEM

To investigate the co-gasification of densified sludge and solid waste, a pilot scale gasification system was designed and constructed. The complete system consists of three subsystems: 1) batch fed downdraft gasifier, 2) data acquisition, and 3) solid waste shredding and densification.

### Batch Fed Downdraft Gasifier

A pilot scale batch fed downdraft gasifier was designed and constructed for the experiments. The design of the gasifier is based on laboratory and pilot scale gasifiers built by the Department of Agricultural Engineering at the University of California, Davis (59,60, and 61).

As shown in Figures 12, 13, and 14, the gasifier is built in three main assemblies, fuel hopper, firebox, and ashpit. The fuel hopper is a double walled cylinder. The inner wall is in the form of a truncated cone to reduce the tendency for fuel bridging. The double wall acts as a condenser to remove water vapor from the fuel prior to gasification. Condensed vapor is collected in a condensate gutter and drained off after each run. The fuel hopper is mounted on the firebox with quick release clamps to allow for easy inspection after experimental runs.

The firebox is also a double walled cylinder. The inner cylinder is the actual firebox. Air is supplied by four air tubes to the annular space between the walls which acts as an air plenum to distribute air evenly to the six tuyeres (air nozzles) which supply air for partial combustion of the fuel. The choke plate acts as a large orifice, replacing the venturi section previously used in earlier World War II and Swedish gasifier designs. The firebox assembly is flange mounted to the ashpit.

The ashpit is used to collect char during an experimental run. A rotating eccentric grate is located in the ashpit immediately below the choke plate. The grate supports the fuel bed, and allows passage of char and gas into the ashpit. Gas is drawn off continuously through a pipe on the side of the ashpit.

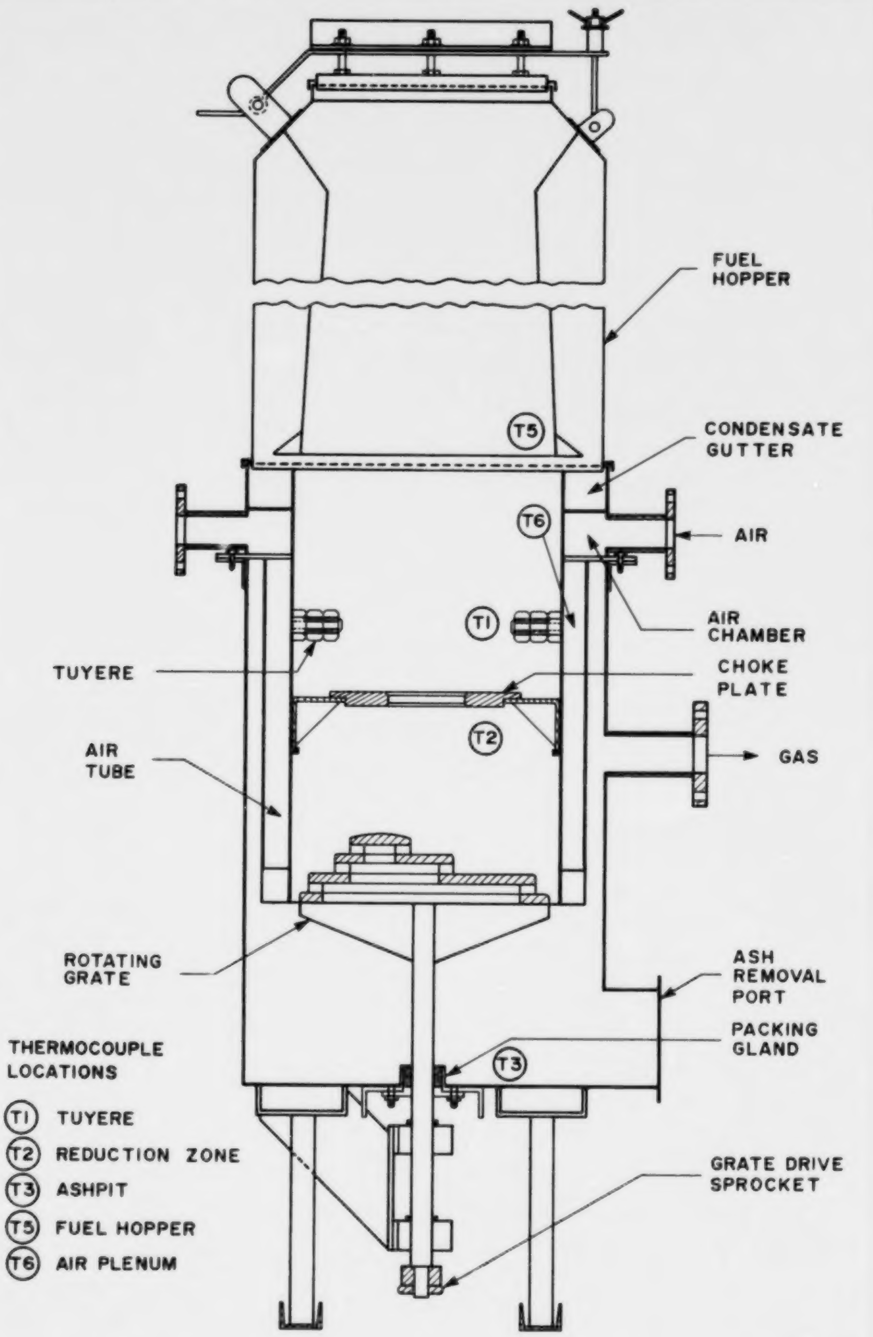
FUEL HOPPER
CONDENSATE GUTTER
AIR
AIR CHAMBER
TUYERE
CHOKE PLATE
AIR TUBE
GAS
ROTATING GRATE
ASH REMOVAL PORT
PACKING GLAND
GRATE DRIVE SPROCKET
T5
T6
T1
T2
T3
THERMOCOUPLE LOCATIONS
T1 TUYERE
T2 REDUCTION ZONE
T3 ASHPIT
T5 FUEL HOPPER
T6 AIR PLENUM

**Figure 12. Cross section - UCD sludge/solid waste gasifier.**

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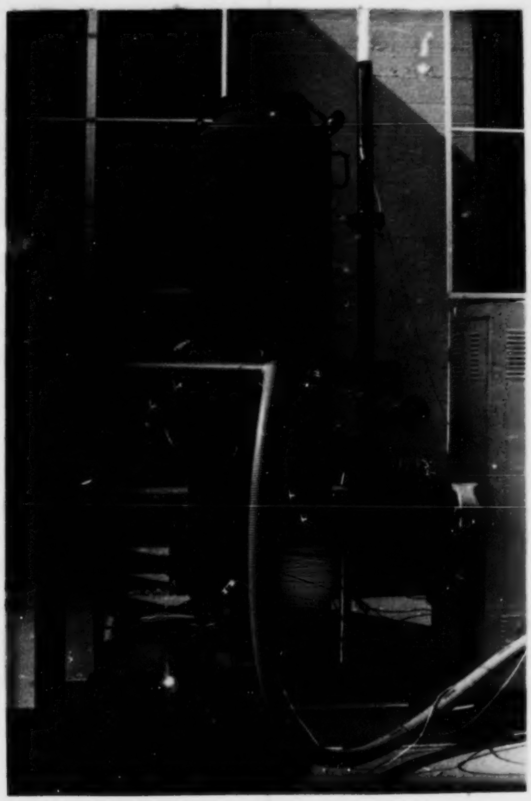

Figure 13. Exterior view - UCD sludge/solid waste gasifier.

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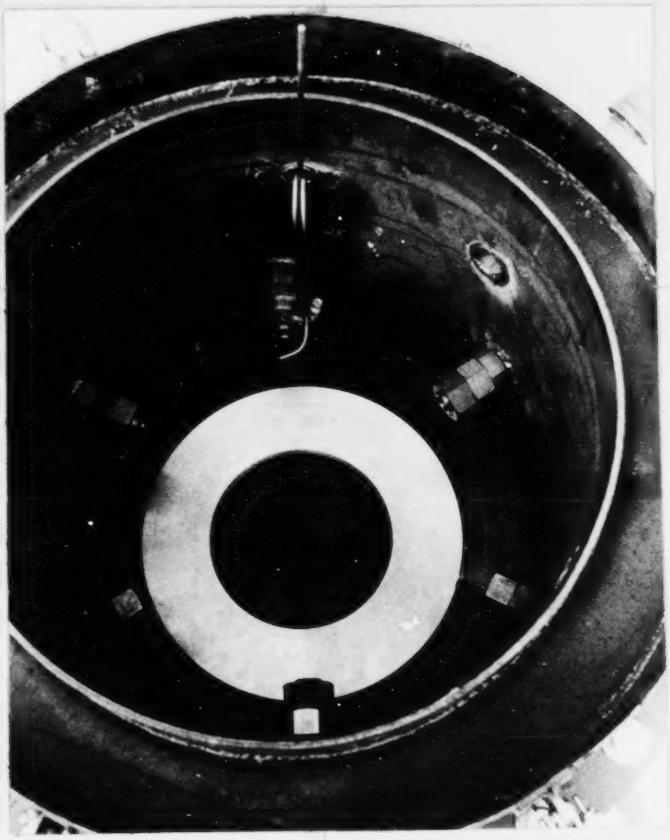

Figure 14. Interior view - UCD sludge/solid waste gasifier.

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**Gasifier Geometry** - Little information is available in the literature concerning the geometric design of a gasifier. The only detailed work on the subject is contained in the report by Nordstrom (39). Between 1957 and 1963 his research group tried various designs and arrived at some empirical relationships between tuyere diameter, tuyere height relative to the venturi section and venturi diameter relative to firebox diameter. Although these experiments were conducted on wood fueled gasifiers, it was felt that Nordstrom's relationships could be used as a guide in the design of a gasifier for solid waste.

Curves presented by Nordstrom (39) were used to estimate the relative sizes of the choke plate, tuyere diameter, tuyere length, and distance between the tuyeres and choke plate. Because the tuyeres, choke plate, and choke support plate and hoop are removable, the internal geometry can be changed easily. The gasifier firebox is 45.7 cm in diameter. In the current configuration of the gasifier, a 7.6 cm choke support hoop, 17.7 cm diameter choke plate, and 6.9 cm long by 1.4 cm inside diameter tuyeres are installed.

**Gasifier Construction** - The choke plates and tuyeres were constructed from Type 304 stainless steel. A temperature resistant alloy, ASTM Type A515 was used for the firebox and the rotating grate. The remainder of the gasifier was constructed from Type 1040 mild steel. Firebrick were not used in the gasifier and the gasifier was not insulated.

The gasifier was constructed in the College of Engineering machine shop. The rolled cylindrical sections, the inner and outer walls of the firebox, the ashpit, and the inner and outer walls of the fuel hopper were fabricated by commercial machine shops. All other cutting, arc welding, and assembly were done in the College of Engineering shops. Full sized gasifiers could easily be constructed in relatively unsophisticated machine shops since exotic materials or complex machining are not required.

## Data Acquisition

The data acquisition subsystem is an automated temperature measurement system. Temperatures are sensed with Type K thermocouples located as shown in Figure 12. Additionally a Type T thermocouple is used in the air inlet line, a Type K thermocouple is installed in the gas outlet pipe, and provision is made for three magnetically mounted Type K thermocouples for surface temperature measurements. Thermal emf from the thermocouples is converted to temperatures by a Digitec Model 1000 Datalogger. Channel number, temperature, and elapsed time are printed on the paper tape output of the instrument. Because it was desired to monitor two critical temperatures on a continuous basis, two additional thermocouple readout devices were installed. These units permit continuous monitoring of the fuel hopper and tuyere temperatures during operation. These temperatures are also recorded automatically by the Datalogger. A schematic of the thermocouple system and a photograph of the complete data analysis subsystem are shown in Figures 15 and 16.

## Solid Waste Shredding and Densification

Densified fuels are required for the operation of fixed bed gasifiers. The simplest type of densification system consists of a shredder followed by an agricultural

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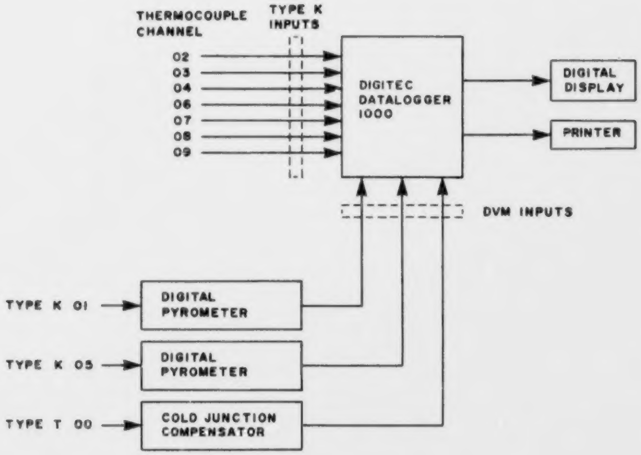
THERMOCOUPLE CHANNEL
TYPE K INPUTS
02
03
04
06
07
08
09
DIGITEC DATALOGGER 1000
DIGITAL DISPLAY
PRINTER
DVM INPUTS
TYPE K 01
DIGITAL PYROMETER
TYPE K 05
DIGITAL PYROMETER
TYPE T 00
COLD JUNCTION COMPENSATOR

Figure 15. Schematic of thermocouple system used to monitor gasifier temperatures.

Figure 16. Data analysis subsystem for monitoring gasifier operation.

type cubing machine. Originally built to produce densified alfalfa hay, these machines can be easily modified to produce solid waste fuel cubes.

Because the capacity of commercially available densification systems is relatively large (1.8 to 4.5 metric tons per hour capacity) compared to the gasifier (16 to 40 kg/hr capacity), a densification system was not built especially for this project. Rather, existing densification systems on the University campus and the pilot plant densification system operated by the Papakube Corporation, San Diego, California were utilized.

**The Cal-Cube Densification System** - The first densification tests were conducted utilizing a Cal-Cube stationary cubing machine located on the campus. Newspaper was shredded with a small hammermill, mixed with lagoon dried sludge (mixture of digested mixed primary and secondary sludge), and fed into the cubing machine by hand. Although acceptable cubes were produced with ground alfalfa, all experiments with sludge/paper mixtures caused jamming of the extrusion dies. Apparently the lignin content of paper produced excessive friction and heat in the dies, forming extremely dense cubes (resembling fiberboard) which jammed the feed mechanism. According to the designer of the machine, installation of shorter extrusion dies would have resolved the problem. However new dies were not available since the machine was no longer in commerical production. Therefore, no further experiments were conducted with this system.

**The John Deere Model 390 Cubing System** - A second densification system on campus was also tested. This machine, a John Deere Model 390 Cubing System, was the same type of machine used in the Ft. Wayne, Indiana tests (21). Because the system is in daily use by the University's Feed Mill to produce feed cubes for experimental disease-free animals, tests with sludge/paper cubes were not permitted. However, a test run with recycled newsprint was conducted. Newsprint was shredded with a hammer mill and fed by hand into the John Deere cuber. Approximately 100 kg of excellent quality cubes were produced. Results of gasification tests with these cubes are discussed in the following chapter. In the Deere machine, cubes are formed by extruding material through extrusion dies with an eccentric rotating presswheel (see Figure 17).

**The Papakube Corporation Densification System** - Based on the successful cubing test with the John Deere cubing machine at the University, the Papakube Corporation was contracted to prepare sludge/solid waste cubes. Key features of the Papakube system include an integral shredder, a metering system which allows moistening the paper to the optimum moisture content, and a modified John Deere Cuber (see Figure 18). The extrusion dies of the machine have been modified with a proprietary coating and finishing treatment which is said to allow the densification of many materials without binding agents (37,38).

## LABORATORY TESTING

Samples of gasifier fuels, chars, and condensate were tested in the laboratory. Grab samples of the low energy gas were also analyzed. The methods used are described in this section. The sampling techniques, apparatus, and methods used for fuel, char, and gas composition are summarized in Table 5.

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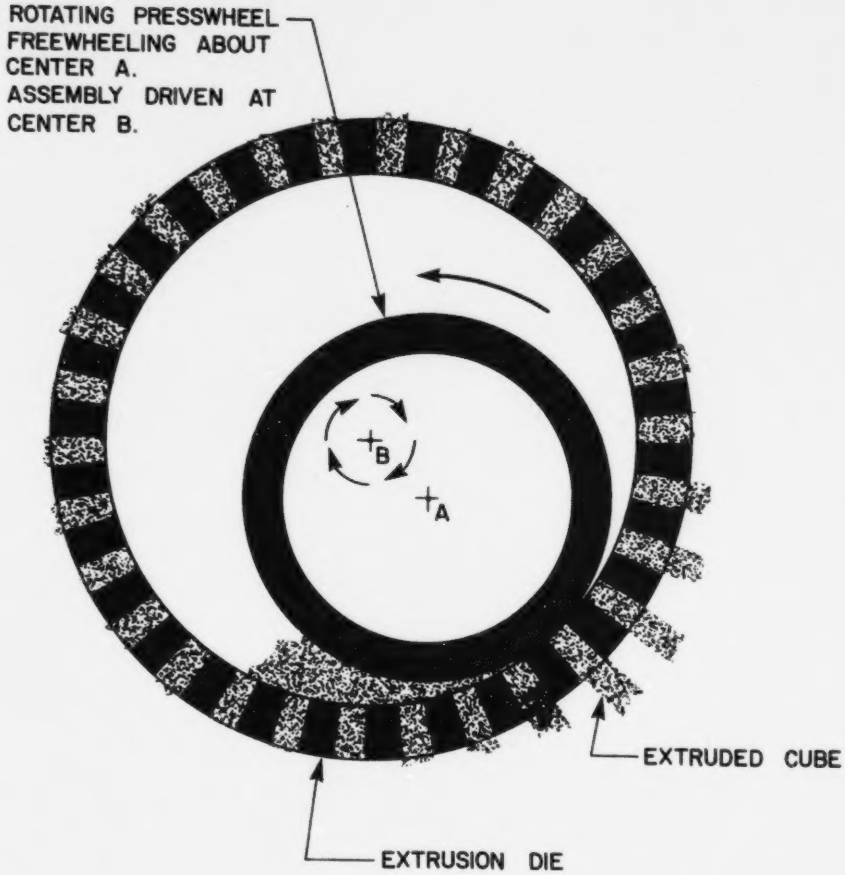
ROTATING PRESSWHEEL FREEWHEELING ABOUT CENTER A.
ASSEMBLY DRIVEN AT CENTER B.
B
A
EXTRUDED CUBE
EXTRUSION DIE

**Figure 17.** Cross section - extrusion dies of the John Deere Cubing Machine. (Adapted from John Deere Model 390 Cubing Machine Catalog)

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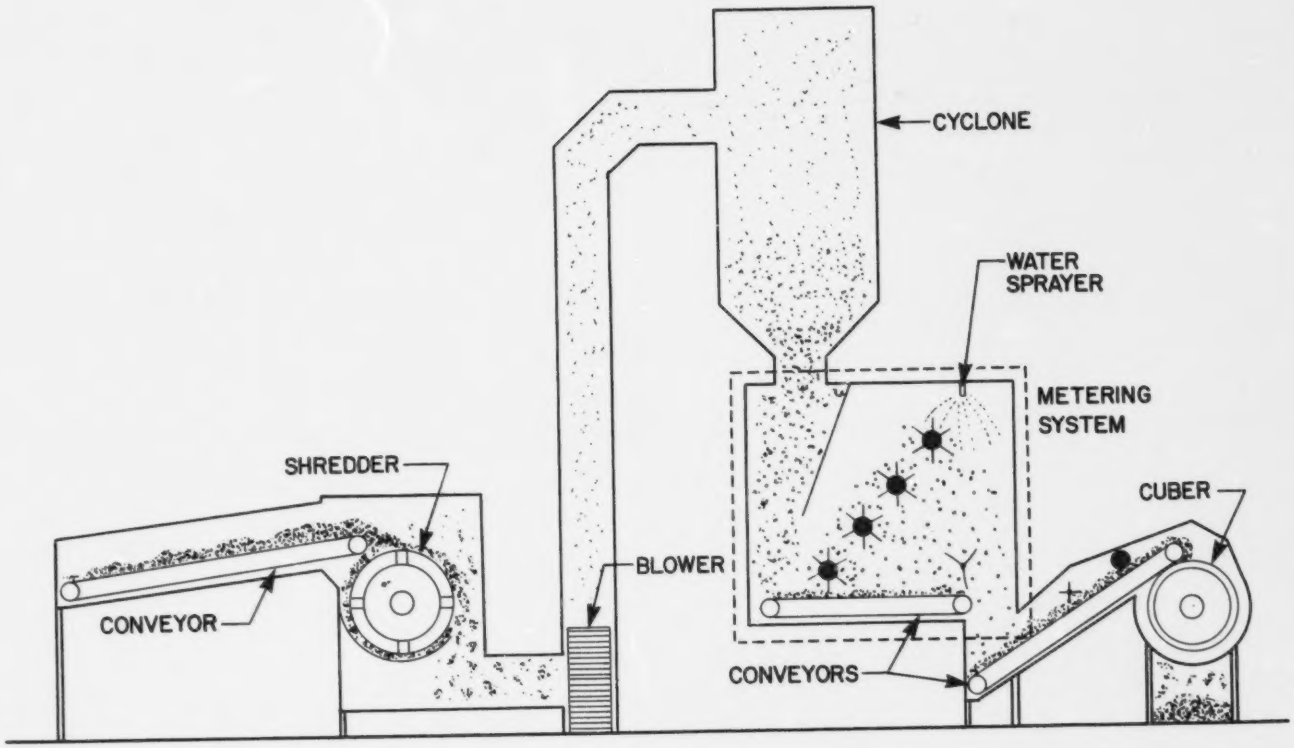
CYCLONE
WATER SPRAYER
METERING SYSTEM
CUBER
SHREDDER
BLOWER
CONVEYOR
CONVEYORS

Figure 18. Schematic of the Papakube densification system.

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## Table 5
## SUMMARY OF DATA COLLECTION AND ANALYSIS EQUIPMENT

| Test | Sampling Technique | Apparatus | Reference |
|---|---|---|---|
| Proximate analysis | Grab samples of fuel and char | Drying oven, muffle furnace, desiccator | ASTM D3172-73<br>"Standard Method for the Proximate Analysis of Coke and Coal" |
| Ultimate analysis | Grab samples of fuel and char | C, H, N w/ Perkin-Elmer Gas Analyzer<br>S by Grote Combustion Method ppt w/ $BaSO_4$ | Micro-Analytical Laboratory<br>Department of Chemistry<br>University of California, Berkeley |
| Energy content | Grab samples of fuel and char | Parr Adiabatic Oxygen Bomb Calorimeter | ASTM D-2015-66<br>"Gross Calorific Value of a Solid Fuel by the Adiabatic Bomb Calorimeter" |
| Dry gas composition | Grab sample of gas | Leeds and Northrup Multi-Component Gas Analyzer ($H_2$, CO, $CO_2$)<br>Leeds & Northrup Thermomagnetic $O_2$ Analyzer<br>Beckman Total Hydrocarbon Analyzer<br>Leeds & Northrup Modular Gas Sampling System | Manufacturers operational manuals. Calibration by standard gas mixtures. See Figure 19 |
| Gas moisture | Grab sample of gas | Ice water impingers, MISCO Model 7200 Source Sampler | Reference 8 and Figure 20 |
| Cube physical properties | Grab sample of fuel | Laboratory balance | Reference 1 |

## Fuel and Char Tests

Proximate analyses of the fuel and char were run using a standard laboratory drying oven, muffle furnace, and analytical balance according to ASTM Standard Methods (see Table 5). Ultimate analysis for percent C, H, N, S, and O of the fuel, char, and condensate was conducted by the Chemistry Department, University of California, Berkeley campus. The energy content of the fuel and char was determined with a Parr Oxygen Bomb Calorimeter.

## Gas Sampling and Analysis

Gas samples were collected in Tedlar gas sampling bags. The gas samples were analyzed on a Leeds and Northrup process analyzer system. Percent by volume on a dry gas basis at ambient temperature were determined for CO, $CO_2$, $O_2$, $H_2$ and total hydrocarbons. Samples were extracted from the gas flare using the sample train shown in Figure 19. Moisture content of the gas was determined by the condensation method as described in Reference 8. The moisture content sampling train is shown in Figure 20.

## FIELD TESTING

In addition to the gasifier temperatures that were recorded automatically by the data analysis subsystem, the following data were recorded manually during test runs.

**Air and Gas Flows** - Air and gas flows were measured using standard flange mounted orifice plates in the air inlet and the gas flare line. The orifice plates were calibrated both before and after each run. Because the gas flare orifice was calibrated with air at ambient temperature, corrections for the temperature and average density of the low energy gas were made.

**Weight Loss** - The entire gasifier is mounted on platform scales. The weight of the gasifier was recorded at five minute intervals. Because only the producer gas leaves the reactor, the weight loss during the run is a direct measure of gas generation.

**Pressure Drop** - The pressure drop across the fuel bed was measured periodically during the run. When the pressure drop exceeded 20 cm of water the grate was rotated, displacing char into the ashpit.

**Char** - Char samples were collected on the day following the run to allow the gasifier to cool. Samples for analysis were collected from the reduction zone when the gasifier was partially disassembled for inspection after each run.

**Condensate** - At the conclusion of each run, condensate was drained from the gasifier, weighed, and a sample saved for later analysis.

**Slag** - To assess the potential of sludge/waste paper cubes to cause slagging, the gasifier was partially disassembled after each run, and the residual char in the firebox removed and sifted for slag agglomerations.

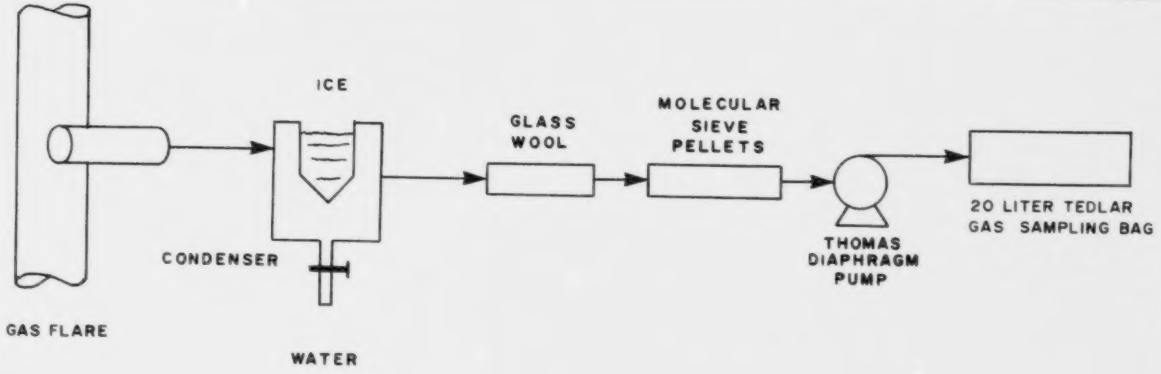
ICE
GLASS WOOL
MOLECULAR SIEVE PELLETS
20 LITER TEDLAR GAS SAMPLING BAG
CONDENSER
THOMAS DIAPHRAGM PUMP
GAS FLARE
WATER

Figure 19. Schematic - dry gas sampling train.

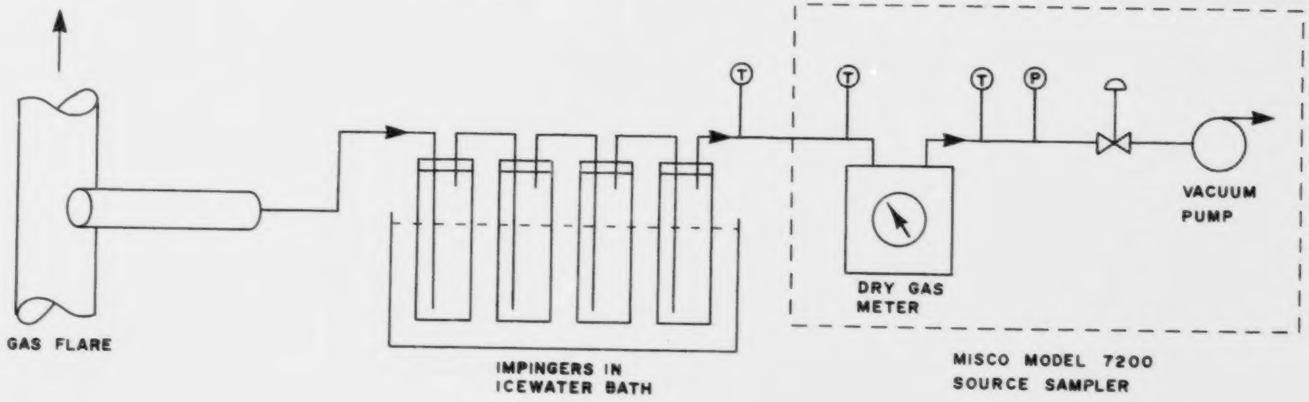
T
T
T
P
VACUUM PUMP
DRY GAS METER
GAS FLARE
IMPINGERS IN ICEWATER BATH
MISCO MODEL 7200 SOURCE SAMPLER

Figure 20. Schematic - gas moisture sampling train.

## PREPARATION OF GASIFIER FUELS

The gasifier was fueled with six different types of fuels: wood chips, an agricultural waste (almond shells), densified sludge/solid waste cubes (Cal-Cube machine), densified solid waste cubes (John Deere machine), and densified solid waste and sludge/solid waste cubes (Papakube system). The preparation of these fuels is described in this section. The characteristics of the fuels are described in a later chapter.

### Wood Chips and Almond Shells

The wood chips and almond shells were both fired in an as received condition. They were obtained from the Agricultural Engineering Department at the University of California, Davis. The wood chips were residues from a kiln dried wood manufacturing operation. The almond shells from a California almond processing plant, were screened to remove fines.

### Densified Sludge/Solid Waste (Cal-Cube Machine)

Samples of source separated newsprint were obtained from the local solid waste contractor, Davis Waste Removal, Inc. The newsprint was shredded with a hand fed hammermill (2.5 cm round hole screen).

The shredded newsprint was mixed in a portable concrete mixer with lagoon dried sludge from the University's sewage treatment plant (about 50 percent solids). Sludge, water, and paper in the proportions of 1:1:8 (on a wet basis) was fed into the Cal-Cube machine by hand. As described previously, only about 50 kg of cubes were made due to mechanical problems with the cubing machine.

### Densified Solid Waste (John Deere Machine)

Source separated newsprint was shredded with a hand fed hammermill and densified with a John Deere Model 390 Stationary Cubing Machine. The shredded newsprint was hand fed into the feed hopper of the machine. About 100 kg of cubes were prepared.

### Densified Sludge/Solid Waste (Papakube System)

Samples of lagoon dried, mixed primary and secondary sludge (approximately 60 percent solids) from the University sewage treatment plant were collected and trucked to the Papakube pilot plant in San Diego. Sludge/solid waste mixtures of 10, 15, 20, and 25 percent sludge (by wet weight) were prepared by placing preweighed sludge and newsprint on the conveyor of the system (see Figure 18). It was assumed that the shredder and blower provided adequate mixing of the sludge and solid waste. Cubes of solid waste alone were also prepared with the Papakube system.

## OPERATIONAL PROCEDURES

A standard operating protocol was used for each test run:

1. **Weigh Empty Gasifier** - The gasifier was weighed prior to fueling. Char from the previous run was left remaining in the gasifier up to the level of the tuyeres to facilitate startup (see Figure 12).

2. **Fuel Gasifier** - The fuel hopper was filled with fuel and the combined weight of the gasifier and fuel recorded.

3. **Turn on Gasification Air** - The blower bypass valve was set to supply to the desired flowrate as measured with the air inlet orifice. The flow was manually regulated during the run with the air bypass valve.

4. **Ignite Gasifier Fuel** - A steel rod was heated red hot with an acetylene torch and inserted into the gasifier ignition port. After smoke was emitted from the flare stack, the rod was removed and the port closed.

5. **Ignite Gas** - After the fuel was ignited, a propane torch was used to ignite the gas from the flare stack.

6. **Record Data** - The gasifier was weighed every 10 minutes, differential and static pressures manually recorded, and temperatures automatically recorded with the Datalogger.

7. **Grate Rotation** - The rotating grate was operated when the pressure drop across the gasifier exceeded 20 cm $H_2O$. Operation of the grate causes the displacement of ash into the ashpit and reduces pressure drop to a normal operating range of 5 to 10 cm $H_2O$.

8. **Gas Moisture Content** - After the gasifier reached steady state conditions as defined by the appearance of the gas flare and the reduction zone temperature, a sample of gas was drawn off for gas moisture content with a MISCO Model 7200 Source Sampler (see Table 5 and Figure 20).

9. **Gas Sample** - Several grab samples of the gas were collected in Tedlar gas sampling bags for later analysis (see Table 5 and Figure 19).

10. **Shut Down** - The blower was turned off after the gas samples were collected. The blower valve was closed to prevent backflow into the blower.

## Post Experimental Run

After completion of each run the standardized procedure outlined below was followed:

1. **Calibrate Orifice Plates** - After allowing the gasifier to cool overnight, the orifice plates were recalibrated to

account for particulate buildup on the plates during the run.

2. **Unload Char** - The rotating grate was run for one minute, then char was unloaded from the ashpit and weighed.

3. **Unload Condensate** - Condensate from the fuel hopper gutter was removed. A sample was obtained for ultimate analysis.

4. **Partial Disassembly** - The fuel hopper was removed from the gasifier by loosening quick release bolts. All unburnt fuel, and char were removed. The gasifier was inspected for corrosion or damage. Samples of char were obtained. All slag was removed, weighed, and retained for later analysis. The char was reloaded into the gasifier to provide a char bed above the level of the tuyeres.

## ENERGY BALANCE COMPUTATIONS

In an energy balance, the energy input to the gasifier is compared with the energy output. Energy inputs include: the sensible and latent heat of the air blast; and the sensible heat and heat of combustion of the fuel. Energy outputs include: the heat of combustion and sensible heat of the dry gas; the sensible and latent heat of the steam in the gas; the sensible heat and heat of combustion of the char; the sensible heat, heat of combustion, and latent heat of the condensate; and convection and radiation losses. Significant data required for mass and energy balances are summarized in Figures 21 and 22. Several simplifications that can be made to the energy balance are discussed below.

### Energy Inputs

The sensible heat of the air blast can be determined by measuring the temperature of the input air. The latent heat of the air blast can be computed by measuring the relative humidity of the ambient air and solving for the absolute humidity at the temperature of the air blast. However, in energy balances conducted on gasification tests of 30 types of agricultural residues, Jenkins (25) found that the sensible and latent heat of the air blast was less than 0.1 percent of the heat of combustion of the fuel. Therefore, the energy input of the air blast was ignored.

The principal input of energy to the gasifier is the heat of combustion of the dry fuel. This must be reduced to account for the heat of vaporization of the bound water in the dry fuel and the free moisture of the fuel as fired. The resultant net energy is defined as:

$$\underset{\text{(MJ/hr)}}{\text{Net energy dry fuel}} = \underbrace{\left[\text{WF} \times \text{FE} \times \left(\frac{100 - \text{MC}}{100}\right)\right]}_{\text{HHV dry fuel (MJ/hr)}} - \underbrace{\left[\text{WF} \times \text{BW} \times \left(\frac{100 - \text{MC}}{100}\right)\right] \times 2.257\,\frac{\text{MJ}}{\text{kg}}}_{\text{Latent heat bound water (MJ/hr)}}$$

$$- \underbrace{\left[\text{WF} \times \left(\frac{100 - \text{MC}}{100}\right)\right] \times 2.257\,\frac{\text{MJ}}{\text{kg}}}_{\text{Latent heat free moisture (MJ/hr)}}$$

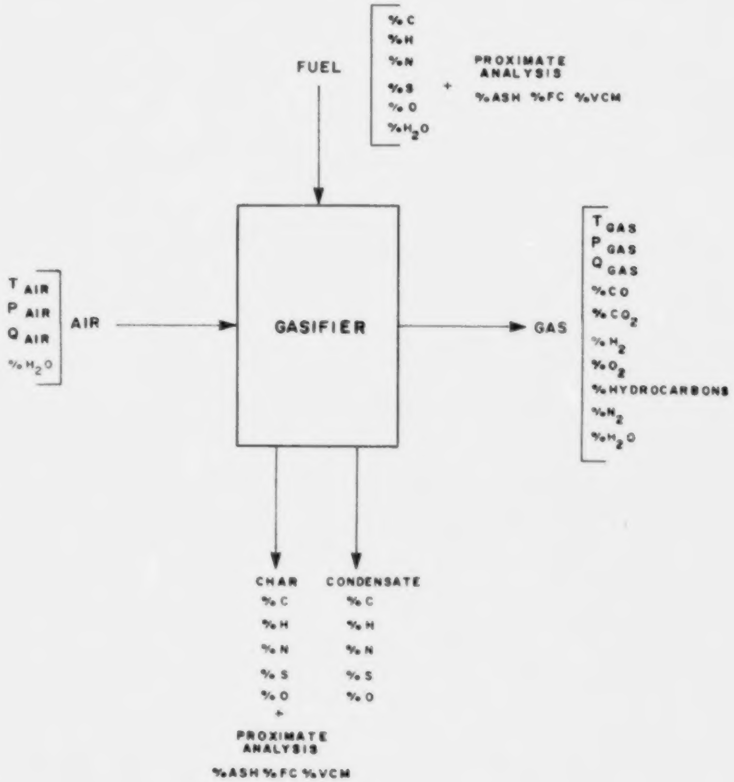
FUEL
%C
%H
%N
%S
%O
%H2O
+
PROXIMATE ANALYSIS
%ASH %FC %VCM
T AIR
P AIR
Q AIR
%H2O
AIR
GASIFIER
GAS
T GAS
P GAS
Q GAS
%CO
%CO2
%H2
%O2
%HYDROCARBONS
%N2
%H2O
CHAR
%C
%H
%N
%S
%O
+
PROXIMATE ANALYSIS
%ASH %FC %VCM
CONDENSATE
%C
%H
%N
%S
%O

Figure 21. Data required for mass balance.

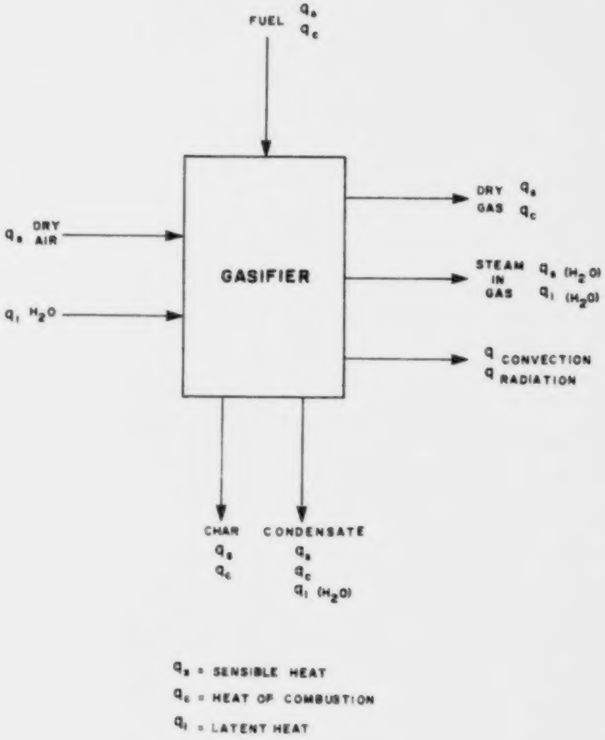
FUEL q_s q_c
q_s DRY AIR
q_l H2O
GASIFIER
DRY GAS q_s q_c
STEAM IN GAS q_s (H2O) q_l (H2O)
q CONVECTION
q RADIATION
CHAR q_s q_c
CONDENSATE q_s q_c q_l (H2O)
q_s = SENSIBLE HEAT
q_c = HEAT OF COMBUSTION
q_l = LATENT HEAT

Figure 22. Data required for energy balance.

where:

WF = wet fuel rate, kg/hr

FE = higher heating value dry fuel, MJ/kg

MC = fuel moisture content, %

2.257 MJ/kg = Latent heat of vaporization of water, 100°C, 1 atmosphere

BW = bound water factor, dimensionless

BW, the bound water factor, is determined from the ultimate analysis of the dry fuel. Two cases are possible:

$$BW = (\%\ O + O/8)/100$$

$$BW = (9 \times \%H)/100$$

The first case is typically encountered in most hydrocarbon fuels such as oil or coal, where all the oxygen in the fuel combines with a portion of the hydrogen to form water upon combustion. Hydrogen is present in excess (called available hydrogen). In the second case, hydrogen is limiting, and excess oxygen exists in the fuel. This is the case with many biomass based fuels such as wood or paper. This computation is made using the computer program ENERGY, which is used to calculate energy balances (see Appendix C).

## Energy Output, Gas

The principal energy output of the gasifier is in the form of low energy gas. The energy in the gas is contained in three forms: chemical energy, sensible heat, and latent heat of the water vapor in the gas.

### Chemical Energy, Gas

The chemical energy of the gas is computed by multiplying the volume fraction of each gas component, as determined by the dry gas analysis, by the lower heating value (LHV) of each component gas, (see Reference 19, p. 1937), and summing the total. Thus, the gas energy content is defined as:

$$\text{Gas energy content } (\text{MJ/m}^3) = X_{CO}E_{CO} + X_{H_2}E_{H_2} + X_{CH_4}E_{CH_4} + X_{C_2H_6}E_{C_2H_6} + X_{CO_2}E_{CO_2} + X_{N_2}E_{N_2}$$

where: $X_{CO}, X_{H_2}, \ldots$ = volume fraction of CO, $H_2$, . . .

$E_{CO}$ = 12.71 MJ/m$^3$ (LHV, dry at 0°C, 762 mm Hg)
$E_{H_2}$ = 10.81 MJ/m$^3$ ( " )
$E_{CH_4}$ = 35.88 MJ/m$^3$ ( " )
$E_{C_2H_6}$ = 63.45 MJ/m$^3$ ( " )
$E_{CO_2}$ = 0 ( " )
$E_{N_2}$ = 0 ( " )

The gas energy content is computed by program "GASEN" (see Appendix A). The program is also used to compute the higher heating value of the gas.

The chemical energy output of the gasifier is defined as:

$$\begin{matrix}\text{Gas} \\ \text{chemical energy} \\ \text{output} \\ \text{(MJ/hr)}\end{matrix} = \begin{bmatrix}\text{Gas energy} \\ \text{content} \\ (\text{MJ/m}^3)\end{bmatrix} \times \begin{bmatrix}\text{Wet gas} \\ \text{flow} \\ (\text{m}^3/\text{min})\end{bmatrix} \times \begin{bmatrix}\dfrac{100\text{-GM}}{100}\end{bmatrix} \times \begin{bmatrix}60\ \dfrac{\text{min}}{\text{hr}}\end{bmatrix}$$

where: GM = gas moisture content, %

**Sensible Heat, Gas** - The sensible heat in the gas is computed by first calculating the mean specific heat at constant pressure for each gas component:

$$\bar{C}_{Pi} = a_i + b_iT + c_iT^2$$

where $\bar{C}_{Pi}$ = molar specific heat for gas component i
$a_i, b_i, c_i$ = specific heat constants for gas component i
$T$ = absolute temperature

The constants $a_i$, $b_i$, $c_i$ can be found in Daniels and Alberty (10), Table 12.

The sensible heat of the gas is the change in enthalpy between the gas exit temperature and a constant reference temperature. For this report, O°C (273 K) was used. To calculate the sensible heat of a gas component, $\Delta H_i$, the equation $dH_i = \bar{C}_{Pi}dT$ is integrated between the reference temperature and, the average gas temperature:

$$\Delta H_i = \int_{273}^{T_1} \bar{C}_P\, dT = \int_{273}^{T_1} (a_i + b_iT + c_i\, T^2)\, dT$$

$$\Delta H_i = a_i (T_1 - 273) + \frac{b_i}{2} (T_1^2 - (273)^2) + \frac{c_i}{3} (T_1^3 - (273)^3)$$

where:
$\Delta H_i$ = sensible heat of gas component
$T_1$ = average gas temperature, K
273 = reference temperature, K

Then the sensible heat of the gas mixture is:

$$\Delta H = \sum_{i=1}^{n} \Delta H_i \cdot X_i$$

where:
$\Delta H$ = sensible heat of gas mixture
$\Delta H_i$ = sensible heat of gas component
$X_i$ = volume fraction of gas component i, volume basis

These calculations are performed with the computer program "GASHEAT" (in the program, $\Delta H$ is assigned the variable name SH, see Appendix B).

**Heat Loss, Condenser** - To utilize low energy gas in an internal combustion engine, the gas must first be dehumidified and cooled. This can be accomplished by passing the moist gas stream through an air or water cooled condenser in which the gas mixture is cooled below its dew point. The process is shown schematically on the idealized psychrometric chart of Figure 23. The gas enters the condenser at dry bulb temperature $T_1$ and is cooled at constant specific humidity from point 1 to 2′, at which point the vapor starts to condense. Further cooling reduces the specific humidity of gas to point 2. The gas exits the condenser in a saturated state at dry bulb temperature $T_2$.

Holman (22) suggested that such a constant pressure cooling process could be treated analytically by writing an energy balance for the condenser system:

$$q = M_g \left[ (h_{g_1} - h_{g_2}) + (\omega_1 h_{v_1} - \omega_2 h_{v_2}) - (\omega_1 - \omega_2) h_f \right]$$

where
$q$ = heat removed by condenser, MJ
$h_{g_1}$ = enthalpy dry gas at $T_1$, MJ/kg
$h_{g_2}$ = enthalpy dry gas at $T_2$, MJ/kg
$\omega_1$ = specific humidity at $T_1$, kg water vapor/kg dry gas

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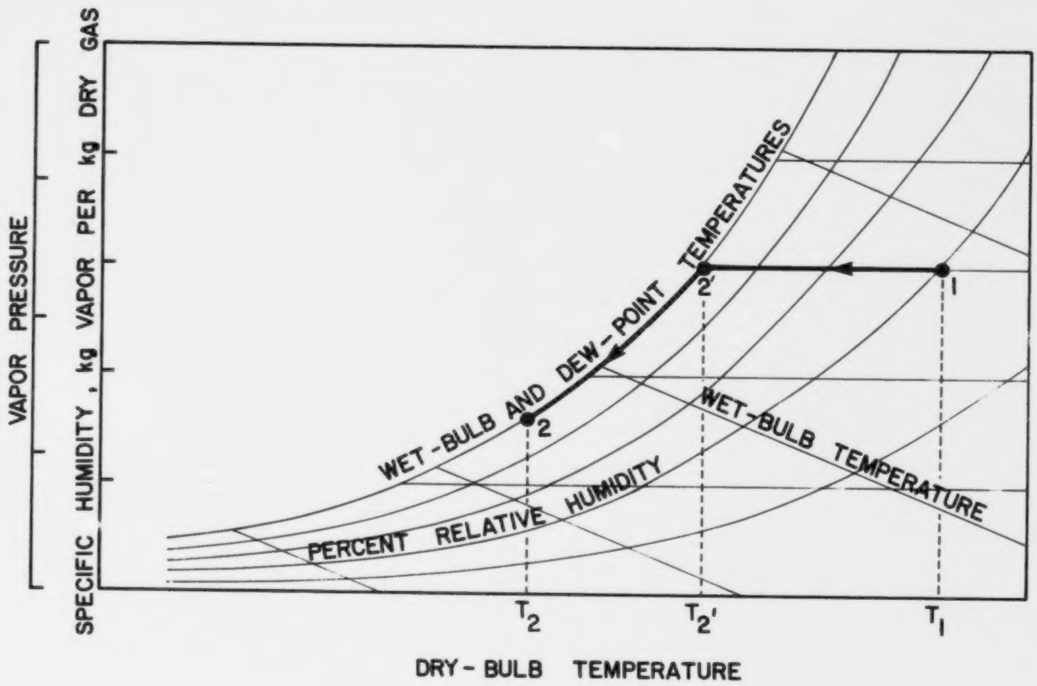


Figure 23. Idealized psychrometric diagram for gas cooling. (After reference 22)

$\omega_2$ = specific humidity at $T_2$, kg water vapor/kg dry gas

$h_{v_1}$ = enthalpy of water vapor at $T_1$, MJ/kg

$h_{v_2}$ = enthalpy of water vapor at $T_2$, MJ/kg

$M_g$ = mass dry gas, kg

$h_f$ = enthalpy of liquid water at $T_2$

The above expression rewritten as a rate expression is:

$$QC = MG\ [\ (h_{g_1} - h_{g_2}) + (\omega_1 h_{v_1} - \omega_2 h_{v_2}) - (\omega_1 - \omega_2)\ h_f]$$

where: QC = heat removed by condenser, MJ/hr

MG = flow rate dry gas, kg/hr

The thermodynamic constants $h_{v_1}$, $h_{v_2}$, and $h_f$ can be found in standard steam tables such as Table A7-M in Holman (22). The term $(h_{g_1} - h_{g_2})$, the change in enthalpy of the dry gas between $T_1$ and $T_2$, is computed in the same fashion as the sensible heat of the wet gas (see previous section). The specific humidity at $T_1$, $\omega_1$, is determined experimentally. The specific humidity at $T_2$, $\omega_2$, is found by assuming that the exit gas is completely saturated. Then:

$$\omega_2 = \frac{P_v}{1.013 - P_v} \cdot \frac{18}{M_{gas}}$$

where: $P_v$ = saturated vapor pressure at $T_2$, bars

1.013 = 1 atmosphere, bars

18 = molecular weight, water vapor, kg

$M_{gas}$ = molecular weight, dry gas, kg

The dry gas flow rate, MG, is determined from the wet gas flow rate as follows:

$$MG = GS\ \frac{M^3}{min} \times 60\ \frac{min}{hr} \times \left(1 - \frac{GM}{100}\right) \times \frac{1}{22.4\ \frac{m^3}{kg\text{-}mole}} \times MD\ \frac{kg}{mole}$$

where:
MG = dry gas flow rate, kg/hr
GS = wet gas flow rate, $m^3$/min (at NTP)
GM = gas moisture content, %
MD = dry gas molecular weight, kg

These calculations are performed with the computer program "GASHEAT" (see Appendix B).

## Energy Output, Char

Energy also leaves the gasifier as sensible heat, latent heat, and heat of combustion of the char. Because cool char is removed from the gasifier on the day following the run, the sensible heat is ignored. The heat of combustion of the char is determined by bomb calorimeter tests. The energy output of the char is defined as:

$$\begin{array}{l}\text{Energy}\\ \text{output}\\ \text{char}\\ (\text{MJ/hr})\end{array} = \begin{bmatrix}\text{Char}\\ \text{generation}\\ \text{rate}\\ (\text{kg/hr})\end{bmatrix} \times \begin{bmatrix}\text{Char}\\ \text{energy}\\ \text{content}\\ (\text{MJ/kg})\end{bmatrix}$$

## Energy Output, Condensate

The condensate is also an energy output. Because condensate is removed from the gasifier at ambient temperature, the latent and sensible heat of the condensate are ignored. The heat of combustion determined by Jenkins (25), 4.75 MJ/kg, is assumed for all runs. The energy output of the condensate is defined as:

$$\begin{array}{l}\text{Energy}\\ \text{output}\\ \text{condensate}\\ (\text{MJ/hr})\end{array} = \begin{bmatrix}\text{Condensate}\\ \text{generation}\\ \text{rate}\\ (\text{kg/hr})\end{bmatrix} \times \begin{bmatrix}4.75\ \text{MJ/hr}\end{bmatrix}$$

## Losses

Energy losses from the gasifier include convection and radiation from the outer surface of the gasifier. Losses are determined by balancing the net energy into the gasifier against the energy outputs. Losses may also reflect errors in determining the gas flow rate and the char generation rate. The energy losses are defined as:

$$\begin{array}{l}\text{Energy}\\ \text{losses}\end{array} = \begin{bmatrix}\text{Net}\\ \text{energy}\\ \text{input}\end{bmatrix} - \begin{bmatrix}\text{Gas}\\ \text{chemical}\\ \text{energy}\\ \text{output}\end{bmatrix} - \begin{bmatrix}\text{Gas}\\ \text{sensible}\\ \text{energy}\\ \text{output}\end{bmatrix} - \begin{bmatrix}\text{Heat}\\ \text{loss,}\\ \text{condenser}\end{bmatrix} - \begin{bmatrix}\text{Char}\\ \text{energy}\\ \text{output}\end{bmatrix} - \begin{bmatrix}\text{Condensate}\\ \text{energy}\\ \text{output}\end{bmatrix}$$

**Efficiencies**

The efficiency of a gasifier can be defined in two ways:

$$\text{Hot gas efficiency} = \frac{\left[\begin{array}{c}\text{Gas chemical}\\ \text{energy output}\end{array}\right] + \left[\begin{array}{c}\text{Gas sensible}\\ \text{energy output}\end{array}\right]}{\left[\begin{array}{c}\text{Net energy}\\ \text{input}\end{array}\right]} \times 100\%$$

$$\text{Cold gas efficiency} = \frac{\left[\begin{array}{c}\text{Gas chemical}\\ \text{energy output}\end{array}\right]}{\left[\begin{array}{c}\text{Net energy}\\ \text{input}\end{array}\right]} \times 100\%$$

The hot gas efficiency is the appropriate figure to use when the sensible heat of the low energy gas can be utilized, such as in direct coupled boiler operation. The cold gas efficiency represents the efficiency that could be expected when the low energy gas is used to power an internal combustion engine, which requires that the gas be cooled, thus wasting the sensible heat.

# CHAPTER IV

# EXPERIMENTAL RESULTS

In the experimental phase of the project the gasifier was operated at a constant air flow rate but fueled with five different types of fuels including: wood chips, almond shells, densified source separated solid waste (two types), and densified mixtures of sludge and solid waste (10, 15, 20, and 25 percent sludge by weight). The characteristics of the fuels, operational data from the test runs, and energy balances for the runs are presented and discussed in this chapter.

## FUEL CHARACTERISTICS

All fuels except the wood chips were tested for proximate analysis, ultimate analysis, and energy content (see Table 5 for the methods used). The results of these analyses are summarized in Table 6. In general, the gasifier fuels tested were all relatively high in volatile combustible matter (VCM), low in carbon content, and low in energy content (HHV) as compared to coal, but similar to Douglas fir and Douglas fir bark (see Table 7).

Both bulk and undividual particle densities of the fuels were also measured (see Table 8). The bulk density is a significant parameter in regards to storage and transportation requirements. The densified fuels are over twice the bulk density of the natural fuels (wood chips and almond shells).

## OPERATIONAL DATA

The results of the gasification test series including the fuel, char, and condensate rates; air and gas flows; weight and volume reductions; and temperature profiles are discussed in this section.

An operational summary of the test series is given in Table 9. All test runs were conducted at as close to the same air flow rate, as possible, 0.41 $m^3$/min (1 atmosphere, 0°C). Thus, the flow rate of fuel through the gasifier, the efficiency, and gas quality are a function of the gasification characteristics of the fuel. The significance of the data in Table 9 is discussed below.

### Fuel, Char, and Condensate Rates

The fuel consumption rate is the primary parameter used to compare the gasification potential of fuels. Since the entire gasifier is mounted on scales, the

## Table 6

## SUMMARY OF FUEL CHARACTERISTICS

| Item | RUN 06A | RUN 06B | RUN 08 |
|---|---|---|---|
| Fuel description | Almond[a] Shells | 10% Sludge[b] Cubes | Solid Waste Cubes |
| Proximate analyses[c] | | | |
| VCM, % | 68.04 | 70.21 | 83.49 |
| FC, % | 20.91 | 12.46 | 7.91 |
| Ash, % | 3.11 | 3.86 | 3.09 |
| Moisture, % | 7.94 | 13.47 | 5.51 |
| Ultimate analyses[d] (Dry basis) | | | |
| C, % | 45.65 | 45.58 | 44.37 |
| H, % | 6.08 | 5.83 | 5.62 |
| N, % | 0.45 | 0.17 | 0.26 |
| S, % | 0.05 | — | 0.05 |
| O, % | 44.57 | 43.92 | 45.90 |
| Residue | 3.20 | 4.50 | 3.80 |
| Energy content[e], MJ/kg (Dry basis, HHV) | 19.08 | 19.03 | 18.92 |

[a] Gasifier initially fueled with almond shells

[b] Gasifier fueled with sludge/solid waste for remainder of RUN 06

[c] Proximate analyses are the average of duplicate grab samples

[d] Ultimate analyses are based on a single grab sample

[e] Bomb calorimeter results are the average of three tests on one grab sample

## Table 6 (cont.)

| Item | RUN 09 | RUN 10 | RUN 11 | RUN 12 |
|---|---|---|---|---|
| Fuel description | 10% Sludge Cubes | 15% Sludge Cubes | 20% Sludge Cubes | 25% Sludge Cubes |
| Proximate analyses | | | | |
| VCM, % | 83.87 | 75.10 | 74.54 | 73.66 |
| FC, % | 8.19 | 12.19 | 13.05 | 13.70 |
| Ash, % | 1.11 | 2.62 | 3.07 | 4.08 |
| Moisture, % | 6.83 | 10.09 | 9.34 | 8.56 |
| Ultimate analyses (Dry basis) | | | | |
| C, % | 46.46 | 45.99 | 45.24 | 45.27 |
| H, % | 5.98 | 5.89 | 5.81 | 5.77 |
| N, % | 0.19 | 0.19 | 0.13 | 0.42 |
| S, % | 0.14 | 0.10 | 0.11 | 0.16 |
| O, % | 45.33 | 44.83 | 46.81 | 44.18 |
| Residue | 1.90 | 3.00 | 1.90 | 4.20 |
| Energy content, MJ/kg (Dry basis, HHV) | 19.04 | 18.88 | 18.93 | 18.49 |

## Table 7

## CHARACTERISTICS OF TYPICAL COALS AND WOODS[a]

| Item | Pittsburgh Seam Coal | Wyoming Elkol Coal | Lignite | Douglas Fir | Douglas Fir Bark |
|---|---|---|---|---|---|
| Proximate analyses (Dry basis) | | | | | |
| VCM, % | 33.9 | 44.4 | 43.0 | 86.2 | 70.6 |
| FC, % | 55.8 | 51.4 | 46.6 | 13.7 | 27.2 |
| Ash, % | 10.8 | 4.2 | 10.4 | 0.1 | 2.2 |
| Ultimate analyses (Dry basis) | | | | | |
| C, % | 75.5 | 71.5 | 64.0 | 52.3 | 56.2 |
| H, % | 5.0 | 5.3 | 4.2 | 6.3 | 5.9 |
| N, % | 1.2 | 1.2 | 0.9 | 0.1 | 0.0 |
| S, % | 3.1 | 0.9 | 1.3 | 0.0 | 0.0 |
| O, % | 4.9 | 16.9 | 19.2 | 40.5 | 36.7 |
| Residue, % | 10.3 | 4.2 | 10.4 | 0.8 | 1.2 |
| Energy content, MJ/kg (Dry basis, HHV) | 31.76 | 29.57 | 24.92 | 21.05 | 22.10 |

[a] After Reference 20

## Table 8

## DENSITIES OF GASIFIER FUELS

| Fuel | Run No. | Densification process | Bulk density kg/m$^3$ | Unit density kg/m$^3$ |
|---|---|---|---|---|
| Wood chips | 02 | Undensified | 230 | --- |
| Almond shells | 06 | Undensified | 187 | --- |
| 10% sludge cubes | 06 | Cal-Cube Machine | 496 | 1009 |
| Solid waste | 08 | John Deere | 484 | 1041 |
| 10% Sludge cubes | 09 | Papakube | 374 | 738 |
| 15% Sludge cubes | 10 | Papakube | 445 | 932 |
| 20% Sludge cubes | 11 | Papakube | 536 | 1010 |
| 25% Sludge cubes | 12 | Papakube | 486 | 1014 |

## Table 9

## OPERATIONAL SUMMARY

| Item | RUN 02 | RUN 06 | RUN 08 |
|---|---|---|---|
| Fuel description | Pine wood chips | Almond shells/ 10% sludge cubes | Solid Waste cubes |
| Fuel consumption rate, kg/hr | 31.3 | 27.2 | 22.8 |
| Char production rate, kg/hr | 2.70 | 2.80 | 2.47 |
| Condensate production rate, kg/hr | 0.19 | 0.18 | 0.67 |
| Net run time, min | 140 | 223 | 221 |
| Gas flare ignition time, min | 1 | 13 | 15 |
| Air input rate, $m^3$/min (0°C, 1 atm) | .410 | .407 | .412 |
| Gas output rate, $m^3$/min (0°C, 1 atm) | N/A[a] | .773 | .627 |
| Average reduction zone temperature, °C | 669.9 | 752.0 | 772.7 |
| Average gas outlet temperature, °C | 164.4 | 197.8 | 214.2 |
| Volume reduction, % | 91 | N/A | 80 |
| Weight reduction, % | 91 | 88 | 86 |

[a] Not available

### Table 9 (Continued)

| Item | RUN 09 | RUN 10 | RUN 11 | RUN 12 |
|---|---|---|---|---|
| Fuel description | 10% Sludge cubes | 15% Sludge cubes | 20% Sludge cubes | 25% Sludge cubes |
| Fuel consumption rate, kg/hr | 21.4 | 12.3 | 17.5 | 16.3 |
| Char production rate, kg/hr | 1.15 | 1.40 | 2.47 | 1.71 |
| Condensate production rate, kg/hr | 0.58 | 0.82 | 0.50 | 0.73 |
| Net run time, min | 251 | 407 | 265 | 262 |
| Gas flare ignition time, min | 9 | 31 | 24 | 44 |
| Air input rate, $m^3$/min (0°C, 1 atm) | .405 | .408 | .407 | .415 |
| Gas output rate, $m^3$/min (0°C, 1 atm) | N/A[a] | N/A | .749 | .735 |
| Average reduction zone temperature, °C | 828.8 | 656.4 | 779.8 | 734.7 |
| Average gas outlet temperature, °C | 193.5 | 149.1 | 197.6 | 180.6 |
| Volume reduction, % | 81 | 73 | 64 | 74 |
| Weight reduction, % | 91 | 80 | 82 | 83 |

[a] Not available

weight loss is recorded at regular intervals during test runs. It is calculated as shown:

$$\text{Fuel consumption rate} = \frac{\begin{bmatrix}\text{Weight loss}\\ \text{during run}\end{bmatrix} + \begin{bmatrix}\text{Condensate}\\ \text{removed}\end{bmatrix} + \begin{bmatrix}\text{Char}\\ \text{removed}\end{bmatrix} + \begin{bmatrix}\text{Slag}\\ \text{removed}\end{bmatrix}}{\begin{bmatrix}\text{Net run time}\end{bmatrix}}$$

Where: Net run time = Run time - (Refueling time + Other down time)

As shown in Table 9, the undensified fuels were consumed at a higher rate than the densified fuels. This result agrees with our original assumption that the fuel consumption rate is inversely related to the bulk density. Run 10, with 15% sludge appears to be an exception. It shows the lowest reaction rate yet it is one of the least dense of the densified fuels. No explanation of this anomaly is evident.

Char and condensate production rates were determined by weighing the char and condensate removed after each run. The differences between the rates for each fuel were not significant.

## Weight and Volume Reduction

In the gasification experiments, the weight reduction for sludge/solid waste cubes ranged from 91 to 83 percent for 10 to 25 percent sludge mixtures, respectively. Similarly, the volume reduction ranged from 64 to 81 percent for 10 to 20 percent sludge mixtures, respectively (see Table 9). Greater volume and weight reductions may be possible by optimization of the gasification process.

## Temperature Profiles

The most important temperatures from an operational viewpoint are the reduction zone and gas outlet temperatures. The temperature of the reduction zone is significant because the principal gasification reactions occur there. The gas outlet temperature is important for the design of gas cleanup equipment and other peripheral devices. It is also used to compute the sensible heat of the gas. The reduction zone thermocouple is mounted just below the choke plate (see Figure 12), and the gas outlet thermocouple is mounted downstream of the gas outlet orifice plate.

Temperature profiles for RUNS 08, 09, 10, 11, and 12 are shown in Figures 24 through 29. The gasifier reduction zone heated rapidly, approaching steady state temperature within 30 to 60 minutes in most cases. The dips in the temperature profiles were due to refueling operations and pauses for the connection of gas sampling equipment. The profiles are similar except for RUNS 10 and 12.

Due to gas sampling problems, RUN 10 was conducted in two parts with 3 hours of down time in between each part. The reduction zone temperature was 843°C when the first part of the run was terminated. When the run was restarted the reduction zone had cooled to 230°C (see Figures 26 and 27). This allowed for an extremely fast restart compared to a cold startup. Thus, fixed bed gasifiers exhibit a heat reservoir effect similar to fluidized bed incinerators.

In RUN 12 difficulty was experienced with igniting the fuel. Once the fuel ignited, the reduction zone temperature curve for RUN 12 had a similar shape to the

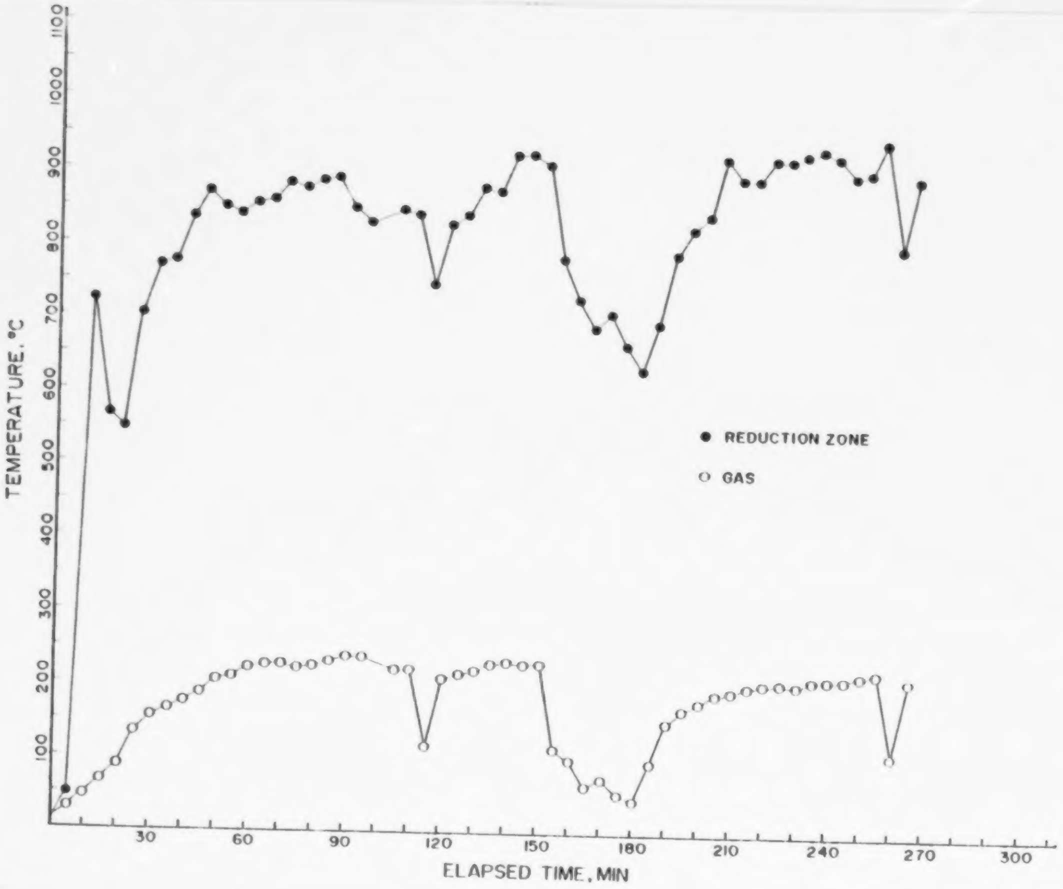


**Figure 24.** Temperature profiles for gasifier reduction zone and low energy gas. (RUN 08)

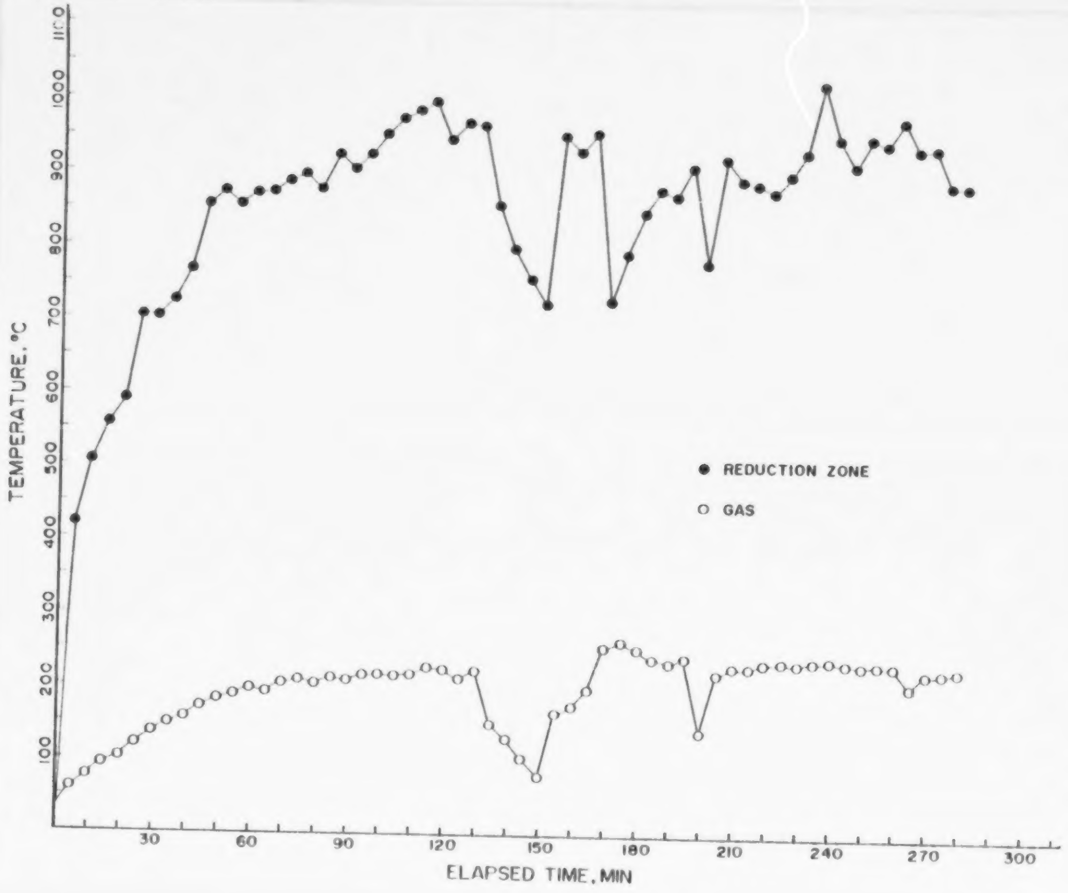


**Figure 25. Temperature profiles for gasifier reduction zone and low energy gas. (RUN 09)**

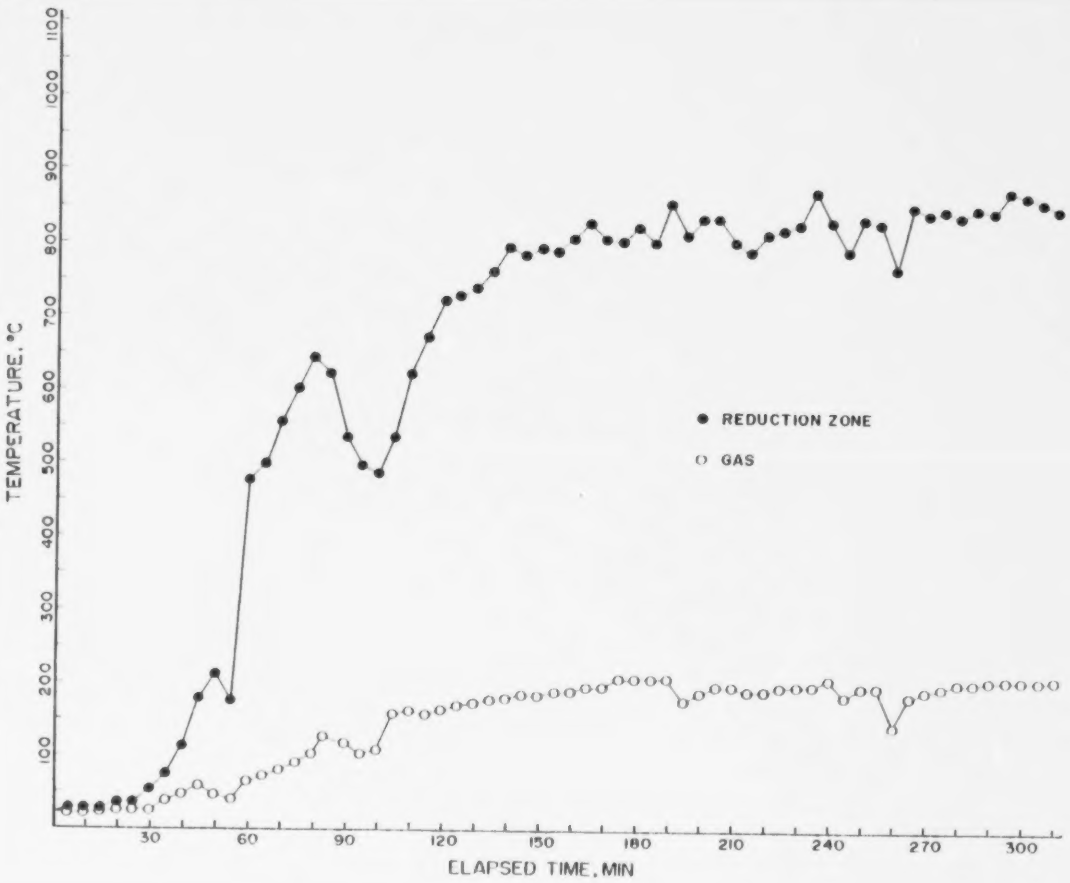


Figure 26. Temperature profiles for gasifier reduction zone and low energy gas. (RUN 10)

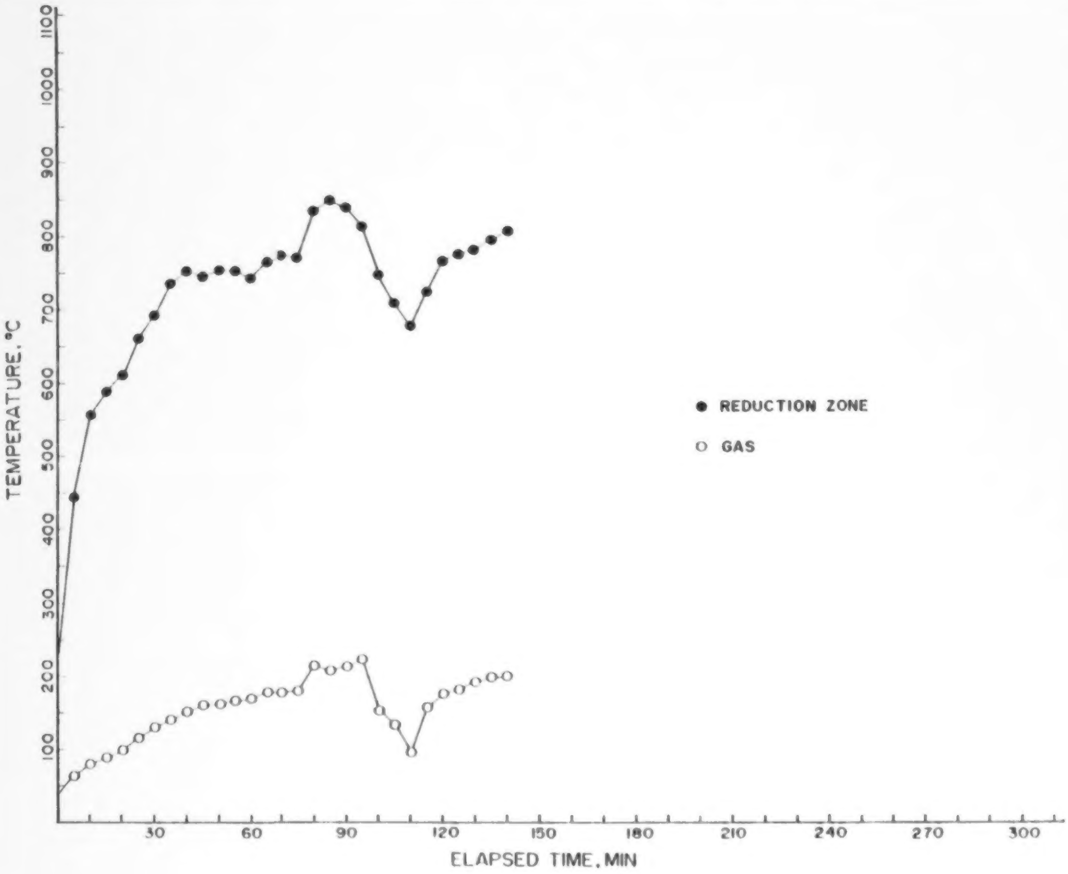


**Figure 27. Temperature profiles for gasifier reduction zone and low energy gas. (RUN 10 continuation)**

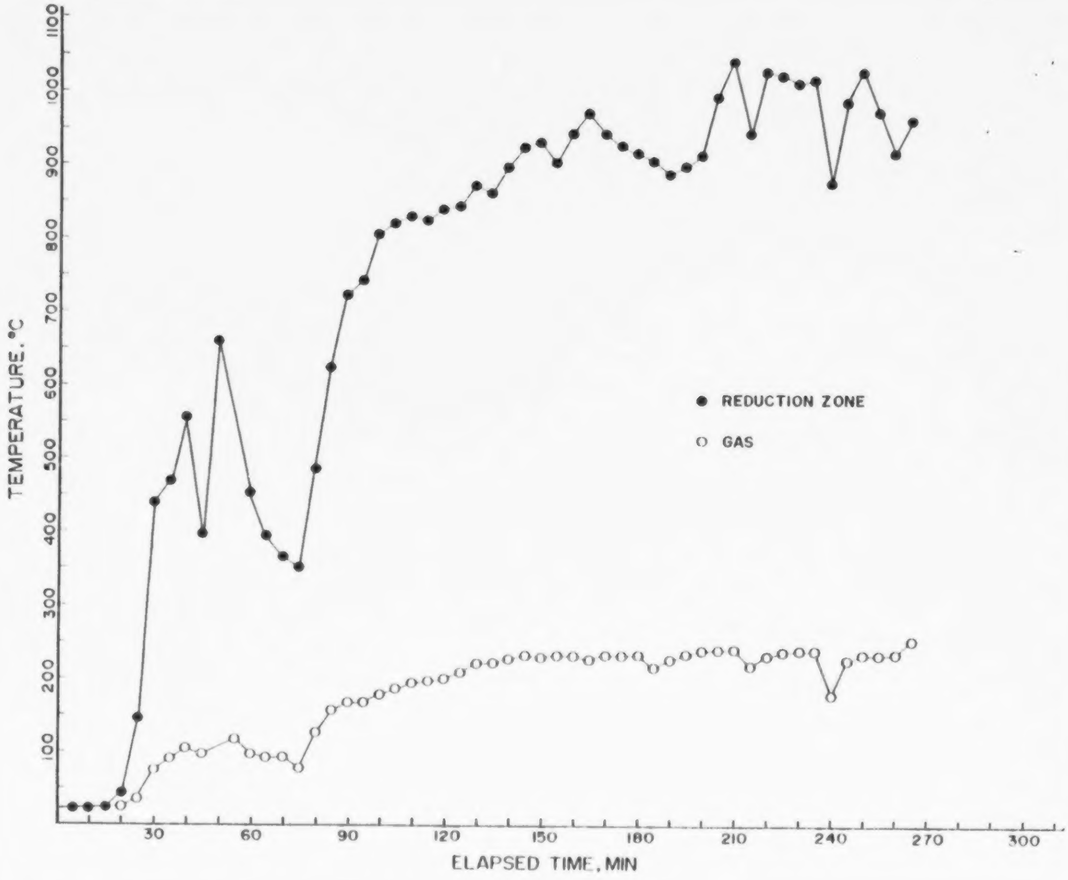


**Figure 28. Temperature profiles for gasifier reduction zone and low energy gas. (RUN 11)**

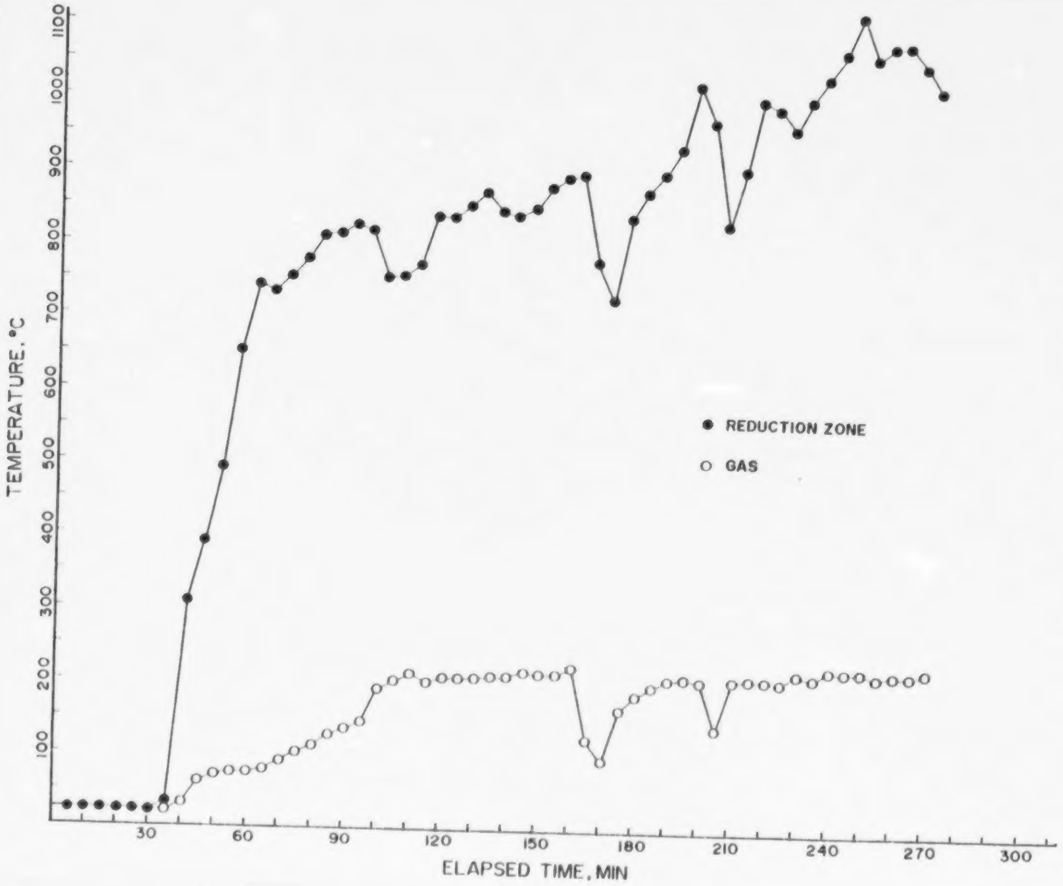


**Figure 29. Temperature profiles for gasifier reduction zone and low energy gas. (RUN 12)**

reduction zone profiles for the other runs (see Figure 29). This problem was alleviated in subsequent test runs by including a 10 cm layer of wood chips or shredded paper in the combustion zone to act as tinder. Also the heated steel rod used for ignition in these runs was replaced with an electric heating element.

## GAS ANALYSES

Gas samples were collected for analysis during RUNS 06 through 12. However, due to problems with the gas sampling train, analyses are only available for RUNS 06, 08, 11, and 12. As described in Chapter III, gas samples were collected in Tedlar gas sampling bags and analyzed off-line with a Leeds and Northrup multicomponent gas analyzer system. Gas moisture content was determined by the condensation method (see Table 5 and Figures 19 and 20). Dry gas composition, gas moisture content, and gas energy content are summarized in Table 10.

The dry gas compositions measured during RUNS 06, 11 and 12 were within the normal range expected for air blown gasifiers. The gas collected in RUN 08 was lower in CO and $H_2$ than expected. This was probably due to a gas leak in the sample train as evidenced by the abnormally high percentage of $O_2$ in the gas. The energy content of the gas samples was within the typical range expected for low energy gas except for RUN 08. However, as previously mentioned, the gas sample collected during RUN 08 was probably contaminated.

## CHAR, CONDENSATE, AND SLAG CHARACTERISTICS

Samples of char and condensate were collected after each run. The char remaining in the ashpit after each run was sifted for slag agglomerations.

### Char

Char samples were collected on the day following the run to allow the gasifier to cool. The rotating grate (see Figure 12) was run for one minute to allow char from the run to fall into the ashpit. During most runs the grate was also rotated when the pressure drop across the gasifier exceeded about 20 cm of water.

Due to the basic design of a fixed bed gasifier, a considerable amount of char must remain inside the gasifier, filling the area between the grate and the top of the tuyere zone. Thus, char sampled from the ashpit may be representative of the previous run and not of the current run. To account for this problem, char samples for analysis were collected from the reduction zone when the gasifier was partially dissembled for inspection after each run.

Significant characteristics of the chars are summarized in Table 11. The proximate analyses of the chars indicates that relative to the gasifier fuels (see Table 6), the chars are low in volatile combustible matter (VCM) and high in fixed carbon (FC). In this respect the chars are similar to coals which are also low in VCM (see Table 7). The ash content of the chars is very high, ranging from 43 to 80 percent. This would limit the use of char as a fuel.

Although char could be blended into the fuel of subsequent runs, a more promising use of the chars may be to utilize them in the polishing of wastewater

## Table 10

## COMPOSITION AND ENERGY CONTENT OF LOW ENERGY GAS

| Item | RUN 06 | RUN 08 | RUN 11 | RUN 12 |
|---|---|---|---|---|
| Dry Gas Composition (By volume) | | | | |
| CO, % | 20.7 | 16.5 | 20.9 | 21.5 |
| $H_2$, % | 16.5 | 12.5 | 14.5 | 13.7 |
| $CH_4$[a], % | 4.8 | 1.9 | 2.3 | 2.5 |
| $C_2H_6$[a], % | 0.2 | 0.1 | 0.1 | 0.1 |
| $CO_2$, % | 11.3 | 8.5 | 11.9 | 11.0 |
| $O_2$, % | 0 | 2.4 | 0.3 | 0.3 |
| $N_2$[b], % | 46.5 | 58.1 | 50.0 | 50.9 |
| Gas Moisture Content (By volume), % | 10.51 | 10.56 | 14.15 | 12.31 |
| Gas Energy Content MJ/$M^3$ (Dry gas, LHV, 0°C, 762 mm Hg) | 6.26 | 4.19 | 5.11 | 5.17 |

[a] Measured as Total Hydrocarbons, $CH_4$ assumed to be 95% of THC, $C_2H_6$ assumed to be 5% of THC

[b] $N_2$ includes nitrogen, argon, and trace amounts of nitrogen oxides. $N_2$ is determined by difference, $N_2 = 100\% - (CO + H_2 + THC + CO_2 + O_2)$

## Table 11

## SUMMARY OF GASIFIER CHAR CHARACTERISTICS

| Item | RUN 06 | RUN 08 | RUN 09 |
|---|---|---|---|
| Fuel description | Almond shells/ 10% sludge cubes | Solid waste cubes | 10% Sludge cubes |
| Proximate analyses | | | |
| VCM, % | 1.23 | 5.51 | 6.50 |
| FC, % | 37.63 | 20.73 | 49.40 |
| Ash, % | 60.89 | 72.57 | 42.90 |
| Moisture, % | 0.25 | 1.19 | 1.20 |
| Ultimate analyses (Dry basis) | | | |
| C, % | 45.31 | 28.81 | 35.78 |
| H, % | 0.48 | 0.29 | 1.00 |
| N, % | 0.20 | 0.17 | 0.21 |
| S, % | 0 | 0.05 | 0.05 |
| O, % | 0 | 3.78 | 0 |
| Residue | 62.2[a] | 66.90 | 64.70[a] |
| Energy content, MJ/kg (Dry basis, HHV) | 13.11 | 8.52 | 22.15 |

[a] As oxides, therefore total is greater than 100%.

## Table 11 (cont.)

| Item | RUN 10 | RUN 11 | RUN 12 |
|---|---|---|---|
| Fuel description | 15% Sludge cubes | 20% Sludge cubes | 25% Sludge cubes |
| Proximate analyses | | | |
| VCM, % | 3.39 | 2.60 | 5.60 |
| FC, % | 46.16 | 16.90 | 18.50 |
| Ash, % | 49.56 | 79.80 | 75.30 |
| Moisture, % | 0.88 | 0.70 | 0.60 |
| Ultimate analyses (Dry basis) | | | |
| C, % | 70.38 | 79.01 | 68.55 |
| H, % | 1.49 | 0.75 | 1.36 |
| N, % | 0.33 | 0.27 | 0.62 |
| S, % | 0.18 | 0.20 | 0.19 |
| O, % | 6.12 | 2.37 | 2.68 |
| Residue | 21.50 | 17.40 | 26.60 |
| Energy content, MJ/kg (Dry basis, HHV) | 24.37 | 27.60 | 24.38 |

treatment plant effluent as a substitute for activated carbon. This possibility is being investigated separately under a research grant from the University of California Appropriate Technology Program (11). Char samples from RUNS 06, 08, 09, 10, 11, and 12, as well as chars from agricultural residues, are being evaluated. Results from this work are not available at this time.

## Condensate

Condensate is produced in the gasifier by condensing vapors formed in the fuel hopper. The vapors are condensed between the double walls of the fuel hopper and collected in a condensate gutter (see Figure 12). At the conclusion of each run, the condensate is drained and a sample saved for analysis. Detailed chemical analyses of the condensate were not conducted, but ultimate analyses for the condensate from six runs are given in Table 12.

In gasification experiments with agricultural wastes, Jenkins (25) found that condensate is about 80 percent water. He also observed that condensate was produced mainly during start-up and shut-down. The average energy content of the condensate was found to be 4.75 MJ/kg.

## Slag

The ash content of a fuel is an important parameter in the evaluation of potential gasifier fuels because of the tendency for high ash content fuels to form slag during the gasification process. Slag formation can reduce fuel flow through the gasifier, increase firebox temperatures, and stress internal parts of the gasifier. In extreme cases, the flow of fuel through the gasifier can be blocked off completely.

To assess the potential of sludge/waste paper cubes to cause slagging, the gasifier was partially disassembled after each run, and the residual char in the firebox removed and sifted for slag agglomerations. The weight of the ash in the fuel and char, and the amount of slag recovered after each run, are summarized in Table 13. In all cases, the ash recovered in the char exceeded the total ash theoretically contained in the fuel consumed during the run. This discrepancy was probably caused by sampling errors as the amount of char generated during a run is not precisely known. The slag generated in each run was approximately half the weight of the ash originally in the fuel. Individual agglomerations were sometimes quite large, exceeding ten centimeters in length. Although no operational problems were experienced with the sludge/solid waste fuels tested, run times were relatively short. Longer test runs will be needed to evaluate the slagging potential of sludge/solid waste mixtures more fully.

Several techniques exist to control slagging. The easiest solution is to limit the ash content of the sludge/solid waste cubes by controlling the ratio of sludge to solid waste. Another technique is to operate the gasifier with a steam/air blast instead of air. This will reduce temperatures in the combustion zone below the point where ash is melted. This method of temperature control is common in coal gasification (18).

## Table 12

## SUMMARY OF CONDENSATE CHARACTERISTICS

|  | Ultimate Analyses, % |  |  |  |  |
|---|---|---|---|---|---|
| RUN | C | H | N | S | O |
| 06 | 12.83 | 9.62 | 0.26 | 0.02 | 77.27 |
| 08 | 7.13 | 10.08 | 0.10 | 0.02 | 82.67 |
| 09 | 7.56 | 10.25 | 0.25 | 0.08 | 81.86 |
| 10 | 7.12 | 10.31 | 0.07 | 0.10 | 82.40 |
| 11 | 6.06 | 10.24 | 0.09 | 0.07 | 83.54 |
| 12 | 7.55 | 10.37 | 0.12 | 0.05 | 81.91 |

## Table 13

## CHAR AND SLAG GENERATION

| Item | RUN | | | |
|---|---|---|---|---|
| | 09 | 10 | 11 | 12 |
| Fuel | | | | |
| Sludge content, % | 10 | 15 | 20 | 25 |
| Ash, % | 1.1 | 2.6 | 3.1 | 4.1 |
| Total fuel, kg | 89.4 | 83.2 | 77.2 | 75.1 |
| Fuel ash, kg | 1.0 | 2.2 | 2.4 | 3.1 |
| Char | | | | |
| Ash, % | 42.9 | 49.6 | 79.8 | 75.3 |
| Total char, kg | 4.8 | 9.5 | 10.9 | 7.5 |
| Char ash, kg | 2.1 | 4.7 | 8.7 | 5.6 |
| Slag | | | | |
| Total slag, kg | 0.6 | 1.2 | 0.8 | 1.0 |
| Totals | | | | |
| Char ash + slag, kg | 2.7 | 5.9 | 9.5 | 6.6 |
| (Char ash + slag)/fuel ash, % | 270 | 270 | 400 | 213 |

## ENERGY BALANCES - RUNS 06, 08, 11, and 12

Energy balances on four runs were calculated using computer programs "GASEN", "GASHEAT", and "ENERGY". The output from the programs "GASEN" and "GASHEAT", the fuel and char characteristics (Tables 6 and 11), and the operational data from each run (Table 9) are used as input to the program "ENERGY", which, in turn, is used to compute energy balances. Listings of the programs and printouts for each run are attached as Appendixes A, B, and C. As previously mentioned, analyses of low energy gas were only available for RUNS 06, 08, 11, and 12. Accordingly, energy balances could only be computed for these runs. A summary of the energy balances is shown in Table 14.

Referring to Table 14, energy balances for each run are given both in energy units, MJ/hr, and percentages, assuming the fuel net energy as 100 percent. The gas chemical energy is the most significant energy output, ranging from 37 to 81 percent of the input net energy. The gas sensible heat is relatively minor, contributing only 3 to 5 percent to the energy output. The gas sensible heat could probably be increased by insulation of the ashpit and gas piping to the flare. A far more significant energy output is the char energy, which ranges from 6 to 25 percent of the input net energy. As char generation is sensitive to fuel residence time and air flow rate, char energy could be minimized by proper operation. Condensate energy is very minor varying from 0.2 to 1.4 percent of the input net energy.

Energy losses ranged from 9 to 49 percent, with 20 percent being typical. The extremely high loss calculated for RUN 08, 49 percent, is most likely due to the inaccurate gas analysis obtained on RUN 08. Hot and cold gas efficiencies ranged from 40 to 37 percent, respectively for RUN 08, to 85 to 81 percent, respectively, for RUN 12. Hot gas efficiencies in the upper 60 percent range are typical for the runs. As mentioned previously, the high losses and low efficiencies calculated for RUN 08 are probably more artifacts of the gas analysis problem with RUN 08, than a measure of the actual performance of the gasifier.

The negative energy losses shown in RUNS 11 and 12 are most likely indicative of errors made in determining the amount of char generated during each run. Due to the relatively large storage volume for char in the gasifier above the grate, it was difficult to exactly determine the amount of char generated during a short (2 to 3 hour) run. This could also account for the apparently lower char generation of RUN 09 (see Table 13).

## Table 14
## ENERGY BALANCES

| Item | RUN 06 |  | RUN 08 |  |
|---|---|---|---|---|
|  | MJ/hr | % | MJ/hr | % |
| Gross Energy, dry fuel | 462.91 |  | 407.61 |  |
| Latent heat, combined water | 27.08 |  | 24.59 |  |
| Latent heat, fuel moisture | 6.57 |  | 2.84 |  |
| Net energy, fuel | 429.25 | 100.00 | 380.18 | 100.00 |
| Gas chemical energy | 259.82 | 60.53 | 140.98 | 37.08 |
| Gas sensible heat | 12.83 | 2.99 | 11.09 | 2.92 |
| Heat loss condenser | 18.40 | 4.29 | 15.78 | 4.15 |
| Char energy | 54.29 | 12.65 | 21.30 | 5.60 |
| Condensate energy | 0.86 | 0.20 | 2.85 | 0.75 |
| Energy losses | 83.05 | 19.35 | 188.18 | 49.50 |
| Hot gas efficiency |  | 63.52 |  | 40.00 |
| Cold gas efficiency |  | 60.53 |  | 37.08 |
| Fuel description | Almond shells/ 10% sludge cubes |  | Solid waste cubes |  |

Table 14 (cont.)

| Item | RUN 11 | | RUN 12 | |
|---|---|---|---|---|
| | MJ/hr | % | MJ/hr | % |
| Gross Energy, dry fuel | 269.49 | | 268.08 | |
| Latent heat combined water | 18.48 | | 16.26 | |
| Latent heat, fuel moisture | 4.15 | | 4.07 | |
| Net energy, fuel | 273.86 | 100.00 | 247.75 | 100.00 |
| Gas chemical energy | 197.15 | 71.99 | 199.93 | 80.70 |
| Gas sensible heat | 12.37 | 4.52 | 11.03 | 4.45 |
| Heat loss condenser | 21.16 | 7.73 | 19.27 | 7.78 |
| Char energy | 69.00 | 25.20 | 41.45 | 16.73 |
| Condensate energy | 2.38 | 0.87 | 3.33 | 1.34 |
| Energy losses | -28.19 | -10.30 | -27.25 | -11.00 |
| Hot gas efficiency | | 76.51 | | 85.15 |
| Cold gas efficiency | | 71.99 | | 80.70 |
| Fuel description | 20% sludge cubes | | 25% sludge cubes | |

# CHAPTER V

# ENGINEERING SIGNIFICANCE

The economic and management issues that must be resolved if the co-gasification process is to be used in a municipal environment are considered in this chapter. These issues include: the economics of co-gasification compared to conventional sludge disposal practices; the role of gasification in large municipalities; the use of co-gasification in small communities; and limitations to the co-gasification process.

## ECONOMICS OF CO-GASIFICATION

Although the gasification process itself is an old one, there is no operating experience available for gasifiers fueled with solid waste operating in a municipal environment. Therefore, to judge the economics of the co-gasification of sludge relative to other more conventional disposal alternatives, many assumptions would have to be made.

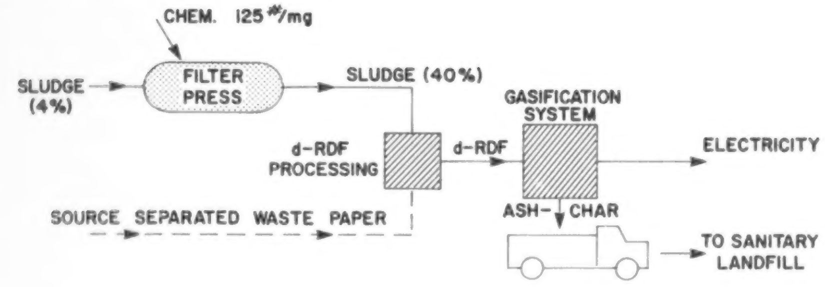
An economic evaluation of co-gasification was made by Bartley (2). He compared a sludge co-gasification system to three conventional sludge processing systems (land application, landfilling, and incineration). The systems studied are shown in Figure 30.

### Sludge Processing and Disposal Alternatives

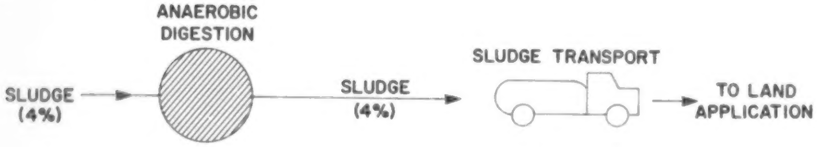
Referring to Figure 30, Option 1, the proposed co-gasification system consists of a source separation program to recover waste paper, a processing system to produce d-RDF from sludge (40 percent solids) and waste paper, a gasifier, and a dual-fuel engine-generator installation to produce electrical power. The ash and char residue from the gasification process will be disposed of in a sanitary landfill. Option 2 involves the land application of digested sludge (4 percent solids) with transport by tank truck and application by subsurface injection. Option 3 provides for the transport of dewatered (20 percent solids) digested sludge by dump truck for disposal to a sanitary landfill. In Option 4 dewatered sludge at 40 percent solids is incinerated autogenously in a multiple hearth furnace, and the resultant ash is hauled to and disposed of in a sanitary landfill.

### Sources of Cost Information

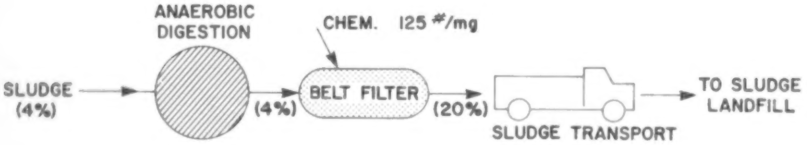
Literature and published reports, communications with manufacturers and equipment suppliers, manufacturers catalogs, and consultations with practicing engineers and researchers were used as sources of information and cost data. Due to the different bases of the cost data obtained from the literature, all literature-derived costs were updated to June 1979. Capital costs of structures and equipment


CHEM. 125 #/mg
SLUDGE (4%)
FILTER PRESS
SLUDGE (40%)
GASIFICATION SYSTEM
d-RDF PROCESSING
d-RDF
ELECTRICITY
SOURCE SEPARATED WASTE PAPER
ASH-CHAR
TO SANITARY LANDFILL

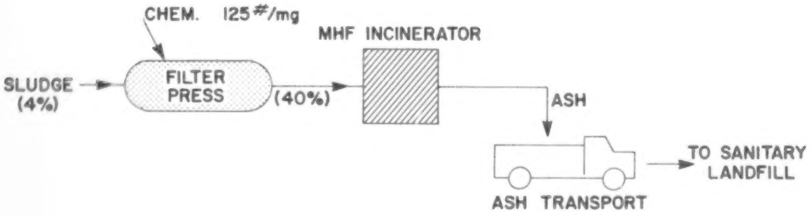
a) Option 1


ANAEROBIC DIGESTION
SLUDGE (4%)
SLUDGE (4%)
SLUDGE TRANSPORT
TO LAND APPLICATION

b) Option 2


ANAEROBIC DIGESTION
CHEM. 125 #/mg
SLUDGE (4%)
(4%)
BELT FILTER
(20%)
TO SLUDGE LANDFILL
SLUDGE TRANSPORT

c) Option 3


CHEM. 125 #/mg
MHF INCINERATOR
SLUDGE (4%)
FILTER PRESS
(40%)
ASH
TO SANITARY LANDFILL
ASH TRANSPORT

d) Option 4

Figure 30. Sludge processing and disposal options.
(After reference 2)

were updated using an Engineering News Record Construction Cost (ENRCC) Index value of 3,000 which corresponds to the value of the Index in June 1979. Other costs were determined using June 1979 labor, power, and fuel costs.

Principal sources of cost data on gasification technology were References 14,40,43,49,55, and 56. Cost data for the conventional processes of digestion, dewatering, incineration, land application, and landfilling were obtained from References 23 and 57. Transportation costs for hauling sludge, char, and ash were developed from Reference 13. Cost estimates for the recovery of source separated waste paper were based on Bartley, et al (3).

## Development of Costs

Bartley (2) calculated operating and capital costs for all four options shown in Figure 30. In developing costs, Bartley made the following generalized assumptions for all four options:

1. Cost of labor is $11/hour including fringe benefits. In cases where operating personnel are not required full time it is assumed they would charge the balance of their time to other operations.
2. Amortization rate is 8 percent.
3. Energy costs are electricity, $0.04/kWh; fuel oil, $0.50/gallon; and vehicle fuel (gasoline and diesel), $1/gallon (June 1979).
4. Annual maintenance of facilities and equipment is 5 percent of the capital cost of the item.

A complete summary of all the assumptions and the computations required is beyond the scope of this thesis. The reader is referred to Bartley (2) for the details. The results of his analysis are summarized below.

## Annual Cost of Sludge Processing and Disposal Options

The annual costs of the four disposal options as a function of distance to disposal site are presented graphically in Figures 31, 32, and 33 for cities of 10,000, 30,000 and 50,000 persons, respectively. The total annual costs of Option 1, the proposed co-gasification system, reflect credit for the value of electrical power produced by the system. The credit amounts to $58,000, $175,000, and $292,000 annually for cities of 10,000, 30,000, and 50,000 persons, respectively (based on an energy credit of $0.04/kWh).

Bartley (2) made the following conclusions on the use of co-gasification (Option 1):

1. The annual costs of Options 2 and 3 (land application of liquid sludge and landfilling of dewatered sludge) are effected significantly by the costs of sludge transport. The transport of liquid sludge in Option 2 results in rapid rise in costs as distance to the disposal site increases. Dewatering sludge prior to transport as in Option 3 decreases overall costs of hauling. Transport costs of the residues from the co-gasification and the incineration options

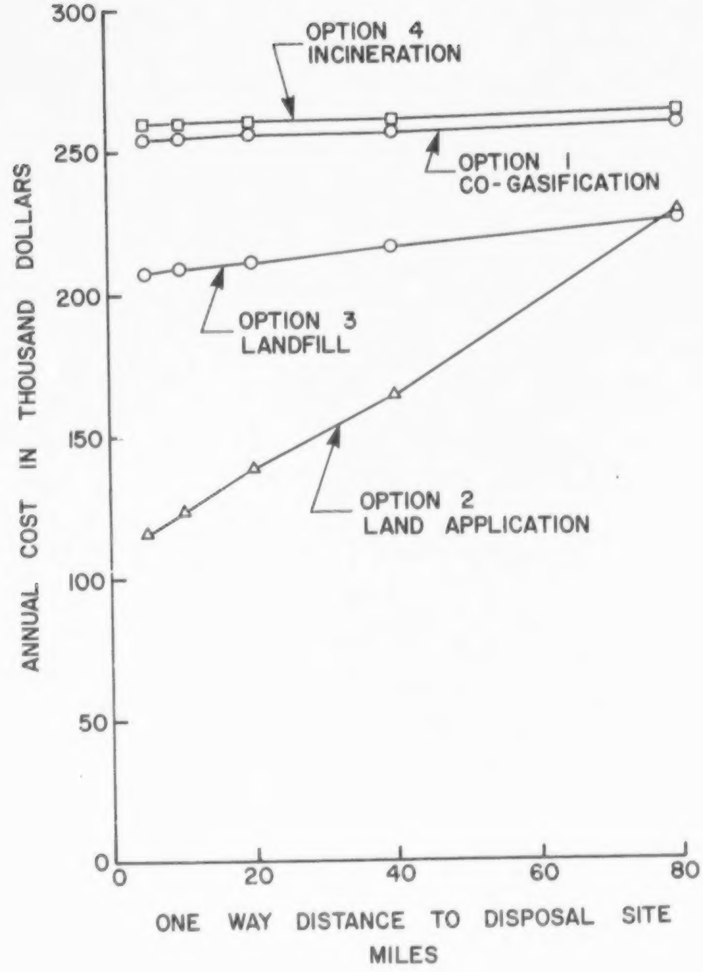


Figure 31. Annual costs of processing and disposal of sewage sludge by various methods of a community of 10,000 persons. (After reference 2)

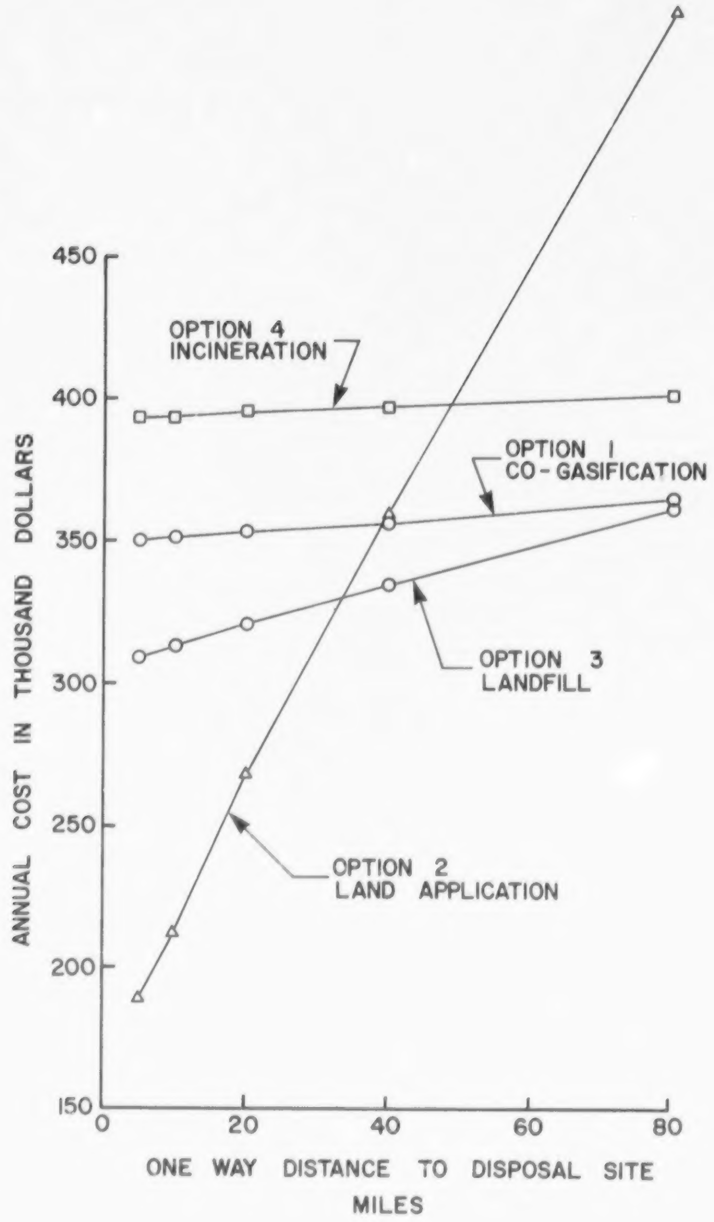


**Figure 32.** Annual costs of processing and disposal of sewage sludge by various methods for a community of 30,000 persons. (After reference 2)

(Options 1 and 4, respectively) do not have significant effect upon annual costs.

2. For cities of 10,000 persons, of the 4 options considered, Option 2, land application of liquid digested sludge, would be least costly when the distance to a disposal site was within approximately 80 miles of the wastewater treatment plant. Beyond 80 miles landfilling of dewatered digested sludge (Option 3) would be more cost effective. Option 1, the proposed co-gasification system, while slightly less costly than the autogenous incineration of dewatered sludge (Option 4), would be less cost effective than either Option 2 and 3.

3. For communities of 30,000 persons, Option 2, land application, would be the most economical system of sludge disposal when the land application site was no more than 30-35 miles distance. Beyond this point Option 3, sludge landfilling, would be more cost effective than Option 2. Option 1, while more costly than Option 3, would have less cost than land application of liquid sludge when the disposal site was 40 miles or more from the community. For disposal site distances greater than 80 miles, Option 1 would be more economical than Option 3.

4. For cities of 50,000 persons, Option 2 is the most favorable option when the disposal site is within about 20 miles from the communities. Beyond 20 miles, Option 1 would be more cost effective than either Option 2 or Option 3. Option 4, incineration, has annual costs greater than Options 1 and 3, but with a disposal site distance greater than approximately 35 miles, the costs of Option 4 are less than Option 2.

## Alternate Gasification Strategies

Because the capital cost of sludge dewatering equipment represents up to 60 percent of the cost of preparing densified gasifier fuels, Bartley (2) looked at the value of low energy gas made from densified paper alone for heating purposes. This approach not only avoids the cost of dewatering but also avoids the high costs of an engine/generator set, which may be 70 percent of the cost of the gasification system.

As shown in Table 15, the cost of producing low energy gas from densified waste paper alone was almost competitive with natural gas prices in mid-1979. Thus, direct use of hot, unfiltered low energy gas in a boiler may be a promising alternate approach to energy recovery instead of the generation of electricity.

## Economic Analysis

Although it would appear from Bartley's (2) analysis that co-gasification is only marginally cost effective, several qualifications must be made to his conclusions:

1. Energy costs were based on mid-1979 values. (electricity $0.04/kWh, fuel oil $0.50/gal, and vehicle fuel (gasoline and diesel) $1.00/gal).

2. Options 1, 3, and 4 utilized mechanical sludge dewatering devices. If alternate lower cost means were used (i.e., lagoons or drying beds), capital and operating costs would change dramatically.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

## Table 15

## COST OF ENERGY OF HOT PRODUCER GAS AND NATURAL GAS[a]

| Fuel | Energy Cost, \$/$10^6$ BTU | | |
|---|---|---|---|
| | Size of community, persons | | |
| | 10,000 | 30,000 | 50,000 |
| Hot, unfiltered producer gas | | | |
| a. Sludge-waste paper d-RDF | 15.35 | 7.90 | 5.91 |
| b. Waste paper d-RDF | 8.62 | 4.00 | 2.98 |
| Natural gas | 2.50 | 2.50 | 2.50 |

[a] After Reference 2

3. The cost of co-gasification were always less than conventional incineration. Also the incineration costs assumed autogenous combustion of the sludge. If this were not the case, expensive auxiliary fuel would be needed in the incineration option.

4. Gasification and densification technology is in a developmental stage. In contrast, conventional sludge processing equipment is well developed. Thus, the costs of gasification equipment may include development costs which have already been amortized in the more mature wastewater treatment industry.

5. Bartley (2) assumed that gasifier char had no value and would be disposed of in a sanitary landfill. If the char has value as a charcoal feedstock or as a low cost substitute for activated carbon (11), the overall cost of gasification would be reduced.

## LARGE SCALE RESOURCE RECOVERY

Until recently, the availability of low cost landfills has negated the necessity of finding alternatives to conventional solid waste disposal practices. It has only been the scarcity and high cost of landfill sites in larger metropolitan areas that has made resource recovery a viable alternative for large scale systems. Such pioneering efforts as those in St. Louis (31) and Baltimore (51) are typical examples of the large scale approach.

### Large Scale Co-disposal of Sludge and Solid Waste

It has become more apparent in recent years that coupling treatment of the liquid and solid waste streams of a community makes good sense from both an economic and technical viewpoint (7). Several of the currently proposed co-disposal systems were described previously in Table 4, Chapter II. These systems have two characteristics in common with the earlier generation of municipal resource recovery projects: they are relatively large scale; and they are technologically complex, employing either mechanically intensive front end systems to produce RDF, or expensive mass fired incinerators to handle unseparated solid waste.

### The Role of Gasification in Large Municipalities

The relative simplicity of the gasification process lends itself to satellite operation in larger cities. For example, source separated solid waste (or sludge/solid waste mixtures) could be densified at a large central facility and trucked to satellite gasifiers in other parts of the city. Or in the case of large urban areas with several landfill sites and wastewater treatment plants, complete co-gasification systems could be located at each site.

## SMALL SCALE GASIFICATION

The technical feasibility of using simple downdraft gasifier to co-dispose of sludge and source separated waste paper, while producing a low energy gas has been demonstrated in this study. The implementation of this technology in a small community setting will require several commitments on the part of the community:

1. An institutional framework must be established for economic and management cooperation between solid waste and wastewater treatment authorities.

2. A community wide source separation system will be required for the production of a suitable gasifier fuel.

3. The technical expertise to manage and operate a co-gasification system will need to be developed, preferably within the existing staff of the solid waste collection and wastewater treatment agencies.

Ultimately, an integrated waste management system, such as shown in Figure 10, Chapter II, could be developed. This would optimize usage of the system and involve rural communities with surrounding agricultural producers. Such a system might also involve the sale of gas, steam, or electricity to local industrial users. Smaller communities could participate by pooling the costs of a central densification system and operating small satellite gasifiers in their own communities to power community owned facilities.

## LIMITATIONS TO THE CO-GASIFICATION PROCESS

The co-gasification of sludge and solid waste is not a panacea. Although gasification itself is an old technology, the application of gasification to municipal uses is a relatively new concept. The hardware needed to implement the concept is manufactured by several firms, but the equipment must still be considered to be in the developmental stage. Questions on the environmental effects of gasification still need to be resolved. Finally, the limitations inherent in the production of low energy gas must be recognized. The gas should be used onsite, most efficiently in a boiler, but can also be used, with an acceptable loss in efficiency, in a gas turbine or internal combustion engine.

Important technical and economic questions that remain to be solved include: optimization of gasifier operation; identification of slag control techniques; determination of the fate of heavy metals in the gasification process; characterization of particulate emissions; economics of co-gasification for small communities; the economic break even point between direct combustion systems and gasification; and the identification of component manufacturers.

## CHAPTER VI

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

An experimental gasifier has been designed, constructed, and operated successfully with a variety of biomass and densified sludge/solid waste fuels. Conclusions derived from the most significant results of this work and recommendations for future research are presented below.

### CONCLUSIONS

Based on the experimental work and a review of the literature in co-disposal and gasification technology, the following conclusions can be drawn:

1. The co-disposal of sludge and solid waste is both economically and technically viable. Several co-disposal facilities are currently under construction in the United States.

2. The preparation of densified sludge/solid waste mixtures at a full scale pilot facility has been demonstrated.

3. A pilot scale downdraft gasifier was designed and constructed. The gasifier design is based on agricultural waste gasifiers built by the Department of Agricultural Engineering at the University of California, Davis.

4. The gasifier was operated with various fuels including an agricultural waste (almond shells), wood chips, densified source separated solid waste, and densified mixtures of sludge and source separated solid waste (10, 15, 20 and 25 percent sludge by wet weight). Low energy gas was produced during the tests with an energy content ranging from 4.19 to 6.26 $MJ/m^3$ at hot gas efficiencies from 40 to 85 percent.

5. The co-gasification of densified sludge and source separated solid waste may be a new approach to co-disposal that could be used by smaller communities. Compared to conventional incineration, co-gasification is cost effective. If mechanical sludge dewatering is used, co-gasification is not competitive with landfilling unless landfill haul

distances exceed 80 miles in communities of 30,000 population, or 15 miles in communities of 50,000 population. If landfill or land application, are viable options, co-gasification does not appear to be feasible for communities of 10,000. The use of alternative sludge drying techniques would substantially reduce the cost of co-gasification.

## RECOMMENDATIONS FOR FUTURE RESEARCH

The technical feasibility of operating a fixed bed gasifier with densified sludge/solid waste mixtures has been demonstrated. However, before the co-gasification process can be considered operational, several key issues must be addressed in future work. They are:

1. The optimum conditions for gasifier operations in terms of fuel consumption, air flow, gas quality, and efficiency need to be defined. These parameters can be used to develop loading factors and specifications for the design of full scale systems.

2. Conditions that cause slagging should be determined. Slag control measures such as steam or water injection, or continuous grate rotation should be investigated.

3. The fate of heavy metals during the gasification process should be determined.

4. Mass emission rates and particle size distributions for particulates in the low energy gas should be measured to provide data for the design of gas cleaning equipment.

5. Emission data from engines, burners, and boilers fueled with low energy gas should be measured. Emissions should also be analyzed for potentially toxic compounds.

6. Manufacturers of system components should be identified. This work will be assisted in part by a forthcoming survey of gasifier manufacturers by the Solar Energy Research Institute (50).

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# APPENDIX A

## COMPUTER PROGRAM "GASEN"

Computer program "GASEN" is written in the BASIC language for the Commodore PET 2001 mini-computer. The program uses dry gas analyses to calculate the energy content of the low energy gas (HHV and LHV) at 60°F, 1 atmosphere and 0°C, 762 mm Hg. Results are reported in both English and metric units. A listing of the program and printouts for the experiment runs are attached. Remark statements (REM) are used throughout the program as comments to the user. Program variables are identified in INPUT statements as they occur.

```
READY.

 5 PRINT"⊐"
 7 PRINT"****************************************"
 9 PRINT"▒▒▒"
 11 PRINT"             PROGRAM GASEN"
 13 PRINT""
 15 PRINT"                  BY"
 16 PRINT""
 17 PRINT"▶▶▶▶▶▶▶▶▶▶▶▶▶▶▶▶SAM VIGIL"
 19 PRINT"":PRINT""
 21 PRINT"              DEC 14, 1980"
 22 PRINT"          REV JAN 25, 1981"
 23 PRINT"▒▒▒"
 24 PRINT"****************************************"
 25 FORI=1TO5000:NEXT:PRINT"⊐"
 27 PRINT"****************************************"
 29 PRINT""
 31 PRINT"PROGRAM GASEN COMPUTES THE LOWER HEATING"
 32 PRINT"VALUE (LHV) AND HIGHER HEATING VALUE":PRINT""
 34 PRINT"(HHV) OF LOW ENERGY GAS FROM THE DRY GAS"
 36 PRINT"ANALYSIS. OUTPUT IS PRINTED IN BOTH SI":PRINT""
 38 PRINT"AND ENGLISH CUSTOMARY UNITS.":PRINT"":PRINT""
 40 PRINT"PLEASE SEE THE PROGRAM LISTING FOR":PRINT""
 42 PRINT"DETAILS.":PRINT""
 44 PRINT"****************************************"
 46 FOR I=1TO8000:NEXT:PRINT"⊐"
 48 REM:LINES 5-44 SET UP TITLES
 50 PRINT"****************************************"
 95 PRINT"▒ENTER RUN #"
 96 INPUT R
 98 PRINT"":PRINT"ENTER DRY GAS ANALYSIS"
 100 PRINT"":PRINT"▒ENTER %CO"
 110 INPUT CO
 120 PRINT"▒ENTER %H2"
 125 INPUT H2
 130 PRINT"▒ENTER %CH4"
 140 INPUT C4
 150 PRINT"▒ENTER %C2H6"
 152 INPUT C2
 154 PRINT"▒ENTER %CO2"
 156 INPUT CD
 158 PRINT"▒ENTER %O2"
 160 INPUT O2
 162 PRINT"▒ENTER %N2"
 164 INPUT N2
 166 PRINT"▒ENTER %H2O"
 168 INPUT AQ
 171 OPEN 4,4
 172 CMD 4
 173 A$="-----------------------------------------------------------"
 174 PRINT A$
 175 PRINT CHR$(1)"GAS ENERGY CONTENT RUN #";R
 176 PRINT A$
 177 PRINT"INPUT DATA - DRY GAS ANALYSIS"
 178 PRINT A$
 180 PRINT"CO  =";CO;"%"
```

```
190 PRINT"H2  =";H2;"%"
200 PRINT"CH4 =";C4;"%"
210 PRINT"C2H6=";C2;"%"
212 PRINT"CO2 =";CD;"%"
214 PRINT"O2  =";O2;"%"
216 PRINT"N2  =";N2;"%"
218 PRINT"H2O =";AQ;"%"
220 DEF FNR(X)=INT(X*100+.5)/100:REM ROUND OFF FUNCTION TO 0.01
222 PRINT A$
224 PRINT"OUTPUT DATA"
226 PRINT A$
228 REM:ENERGY CONTENT VALUES FROM "HANDBOOK OF CHEMISTRY AND PHYSICS",42ND ED
230 REM:C.D. HODGMAN, EDITOR-IN-CHIEF,THE CHEMICAL RUBBER PUBLISHING CO.,
232 REM:CLEVELAND, OHIO,1961,(P1937).
234 H1=(CO*322.6+H2*324.5+C4*1013.2+C2*1792)/100
236 PRINT"HHV DRY GAS = ";FNR(H1);"BTU/FT3,(30 IN HG,60 DEG F)"
238 HM=H1*.037259:REM CONVERTS BTU/FT3 TO MJ/M3
240 PRINT"HHV DRY GAS = ";FNR(HM);"MJ/M3,(30 IN HG,60 DEG F)":PRINT""
242 L1=(CO*322.6+H2*275.0+C4*913.1+C2*1641)/100
244 PRINT"LHV DRY GAS = ";FNR(L1);"BTU/FT3,(30 IN HG,60 DEG F)"
246 L2=L1*.037259:REM CONVERTS BTU/FT3 TO MJ/M3
248 PRINT"LHV DRY GAS = ";FNR(L2);"MJ/M3,(30 IN HG,60 DEG F)":PRINT""
250 H3=(CO*341.0+H2*343.0+C4*1069+C2*1862)/100
252 PRINT"HHV DRY GAS = ";FNR(H3);"BTU/FT3,(30 IN HG,0 DEG C)"
254 H4=H3*.037259:REM CONVERTS BTU/FT3 TO MJ/M3
256 FRINT"HHV DRY GAS = ";FNR(H4);"MJ/M3,(30 IN HG,0 DEG C)":PRINT""
258 L3=(CO*341.0+H2*290.0+C4*963.0+C2*1703)/100
260 PRINT"LHV DRY GAS = ";FNR(L3);"BTU/FT3,(30 IN HG,0 DEG C)"
262 L4=L3*.037259:REM CONVERTS BTU/FT3 TO MJ/M3
264 PRINT"LHV DRY GAS = ";FNR(L4);"MJ/M3,(30 IN HG,0 DEG C)"
266 PRINT A$
268 PRINT#4:CLOSE 4
270 REM:LHV VALUES FOR LINE 242 FROM "CHEMICAL ENGINEERS HANDBOOK",
272 REM:5TH EDITION,R.H. PERRY & C.H. CHILTON,EDITORS,
274 REM:MCGRAW-HILL BOOK CO.,NEW YORK,1973.
276 END
READY.
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-----------------------------------------------------
GAS ENERGY CONTENT RUN # 6
-----------------------------------------------------
INPUT DATA - DRY GAS ANALYSIS
-----------------------------------------------------
CO   = 20.7 %
H2   = 16.5 %
CH4 = 4.8 %
C2H6= .2 %
CO2 = 11.3 %
O2   = 0 %
N2   = 46.5 %
H2O = 10.51 %
-----------------------------------------------------
OUTPUT DATA
-----------------------------------------------------
HHV DRY GAS =  172.54 BTU/FT3,(30 IN HG,60 DEG F)
HHV DRY GAS =  6.43 MJ/M3,(30 IN HG,60 DEG F)

LHV DRY GAS =  159.26 BTU/FT3,(30 IN HG,60 DEG F)
LHV DRY GAS =  5.93 MJ/M3,(30 IN HG,60 DEG F)

HHV DRY GAS =  182.22 BTU/FT3,(30 IN HG,0 DEG C)
HHV DRY GAS =  6.79 MJ/M3,(30 IN HG,0 DEG C)

LHV DRY GAS =  168.07 BTU/FT3,(30 IN HG,0 DEG C)
LHV DRY GAS =  6.26 MJ/M3,(30 IN HG,0 DEG C)
-----------------------------------------------------
```

```
-----------------------------------------------------
GAS ENERGY CONTENT RUN # 8
-----------------------------------------------------
INPUT DATA - DRY GAS ANALYSIS
-----------------------------------------------------
CO   = 16.5 %
H2   = 12.5 %
CH4 = 1.9 %
C2H6= .1 %
CO2 = 9.5 %
O2   = 2.4 %
N2   = 58.1 %
H2O = 10.56 %
-----------------------------------------------------
OUTPUT DATA
-----------------------------------------------------
HHV DRY GAS =  114.83 BTU/FT3,(30 IN HG,60 DEG F)
HHV DRY GAS =  4.28 MJ/M3,(30 IN HG,60 DEG F)

LHV DRY GAS =  106.59 BTU/FT3,(30 IN HG,60 DEG F)
LHV DRY GAS =  3.97 MJ/M3,(30 IN HG,60 DEG F)

HHV DRY GAS =  121.31 BTU/FT3,(30 IN HG,0 DEG C)
HHV DRY GAS =  4.52 MJ/M3,(30 IN HG,0 DEG C)

LHV DRY GAS =  112.52 BTU/FT3,(30 IN HG,0 DEG C)
LHV DRY GAS =  4.19 MJ/M3,(30 IN HG,0 DEG C)
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GAS  ENERGY  CONTENT  RUN  #  11
----------------------------------------------------
INPUT DATA - DRY GAS ANALYSIS
----------------------------------------------------
CO  = 20.9 %
H2  = 14.5 %
CH4 = 2.3 %
C2H6= .1 %
CO2 = 11.9 %
O2  = .3 %
N2  = 50 %
H2O = 14.15 %
----------------------------------------------------
OUTPUT DATA
----------------------------------------------------
HHV DRY GAS =  139.57 BTU/FT3,(30 IN HG,60 DEG F)
HHV DRY GAS =  5.2 MJ/M3,(30 IN HG,60 DEG F)

LHV DRY GAS =  129.94 BTU/FT3,(30 IN HG,60 DEG F)
LHV DRY GAS =  4.84 MJ/M3,(30 IN HG,60 DEG F)

HHV DRY GAS =  147.45 BTU/FT3,(30 IN HG,0 DEG C)
HHV DRY GAS =  5.49 MJ/M3,(30 IN HG,0 DEG C)

LHV DRY GAS =  137.17 BTU/FT3,(30 IN HG,0 DEG C)
LHV DRY GAS =  5.11 MJ/M3,(30 IN HG,0 DEG C)
----------------------------------------------------
```

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```
----------------------------------------------------
GAS  ENERGY  CONTENT  RUN  #  12
----------------------------------------------------
INPUT DATA - DRY GAS ANALYSIS
----------------------------------------------------
CO  = 21.5 %
H2  = 13.7 %
CH4 = 2.5 %
C2H6= .1 %
CO2 = 11 %
O2  = .3 %
N2  = 50.9 %
H2O = 12.31 %
----------------------------------------------------
OUTPUT DATA
----------------------------------------------------
HHV DRY GAS =  140.94 BTU/FT3,(30 IN HG,60 DEG F)
HHV DRY GAS =  5.25 MJ/M3,(30 IN HG,60 DEG F)

LHV DRY GAS =  131.5 BTU/FT3,(30 IN HG,60 DEG F)
LHV DRY GAS =  4.9 MJ/M3,(30 IN HG,60 DEG F)

HHV DRY GAS =  148.89 BTU/FT3,(30 IN HG,0 DEG C)
HHV DRY GAS =  5.55 MJ/M3,(30 IN HG,0 DEG C)

LHV DRY GAS =  138.82 BTU/FT3,(30 IN HG,0 DEG C)
LHV DRY GAS =  5.17 MJ/M3,(30 IN HG,0 DEG C)
----------------------------------------------------
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(PREVIOUSLY CIN. EPA FORM 337)
TYPING GUIDE SHEET

# APPENDIX B

## COMPUTER PROGRAM "GASHEAT"

Computer program "GASHEAT" is written in the BASIC language for the Commodore PET 2001 mini-computer. The program uses the dry gas analysis, gas moisture content, average gas flow, average gas temperature, average condenser temperature and thermodynamic data from standard tables to calculate the sensible heat of the low energy gas and the latent heat lost when the gas is condensed. A list of the program and printouts for the experimental runs are attached. Remark (REM) statements are used throughout the program as comments to the user. Program variables are identified in INPUT statements as they occur.

```
1 PRINT"J"
10 PRINT"****************************************"
11 PRINT"▒▒▒▒▒"
12 PRINT"            PROGRAM GASHEAT"
14 PRINT""
16 PRINT""
18 PRINT"                  BY"
20 PRINT""
21 PRINT"              SAM VIGIL"
22 PRINT""
23 PRINT"                  &"
24 PRINT""
25 PRINT"             NELSON SORBO"
26 PRINT"":PRINT""
27 PRINT"             SEPT 23,1980"
29 PRINT"▒▒"
30 PRINT"****************************************"
32 FOR I=1TO5000:NEXT:PRINT"J"
34 PRINT"****************************************"
36 PRINT"▒▒"
38 PRINT"PROGRAM GASHEAT COMPUTES THE HEAT LOSS":PRINT""
40 PRINT"FROM A CONDENSER AND THE SENSIBLE":PRINT""
41 PRINT"HEAT OF THE WET GAS."
42 PRINT"▒▒▒▒"
44 PRINT"PLEASE SEE THE PROGRAM LISTING FOR":PRINT""
46 PRINT"DETAILED INFORMATION.
48 PRINT"▒▒▒▒"
49 PRINT"****************************************"
50 FOR I=1TO8000:NEXT:PRINT"J"
52 REM LINES 10-50 SET UP TITLES
121 PRINT"J":PRINT"▒ENTER RUN NUMBER":INPUT RU
122 PRINT"ENTER DRY GAS ANALYSIS AND GAS M/C"
130 PRINT "▒ENTER %CO":INPUT X1
200 PRINT "▒ENTER %H2":INPUT X2
280 PRINT "▒ENTER %CH4":INPUT X3
300 PRINT "▒ENTER %C2H6":INPUT X4
320 PRINT "▒ENTER %CO2":INPUT X5
340 PRINT "▒ENTER %O2":INPUT X6
360 PRINT "▒ENTER %N2":INPUT X7
362 PRINT"▒ENTER %H2O":INPUT X8
364 DEF FNR(X)=INT(X*10+.5)/10:REM ROUND OFF FUNCTION TO 0.1
365 DEF FNX(X)=INT(X*100+.5)/100:REM ROUND OFF FUNCTION TO 0.01
366 REM LINES 368-382  CONVERT THE DRY GAS ANALYSIS TO A WET GAS BASIS
368 Y1=X1*(100-X8)/100:Y1=FNR(Y1)
370 Y2=X2*(100-X8)/100:Y2=FNR(Y2)
372 Y3=X3*(100-X8)/100:Y3=FNR(Y3)
374 Y4=X4*(100-X8)/100:Y4=FNR(Y4)
376 Y5=X5*(100-X8)/100:Y5=FNR(Y5)
378 Y6=X6*(100-X8)/100:Y6=FNR(Y6)
380 Y7=X7*(100-X8)/100:Y7=FNR(Y7)
382 Y8=X8:REM GAS MC IS THE SAME IN BOTH THE WET & DRY GAS ANALYSIS
383 PRINT "▒ENTER AVG GAS TEMP DEG C":INPUT T1
384 PRINT "▒ENTER AVG COND TEMP DEG C":INPUT T2
385 PRINT"▒ENTER ENTHALPY SAT VAPOR AT T1, MJ/KG":INPUT H1
386 PRINT"▒ENTER ENTHALPY SAT VAPOR AT T2, MJ/KG":INPUT H2
387 PRINT"▒ENTER ENTHALPY SAT WATER AT T2, MJ/KG":INPUT HF
```

```
388 PRINT"♥ENTER SAT VAPOR PRESSURE AT T2, BARS":INPUT PV
389 REM FOR LINES 380-385, SEE TABLE A-7M,PAGE 718
390 REM "THERMODYNAMICS",THIRD ED.,BY J.P. HOLMAN
391 PRINT"♥ENTER WET GAS FLOW M3/MIN"
392 PRINT"♥AT NTP (0 DEG C, 1 ATM)":INPUT GS
393 OPEN 4,4
394 CMD 4
395 A$="---------------------------------------------------------"
396 PRINT A$
397 PRINT CHR$(1)"GAS SENSIBLE & LATENT HEAT"
398 PRINT CHR$(1)"RUN #";RU
399 PRINT A$
400 PRINT"INPUT DATA"
401 PRINT A$
402 PRINT"GAS FLOW =";FNX(GS);"M3/MIN"
404 PRINT"GAS TEMP =";FNX(T1);"DEG C"
406 PRINT"COND TEMP=";FNX(T2);"DEG C"
408 PRINT"ENTHALPY SAT VAPOR AT T1 = ";H1;"MJ/KG"
410 PRINT"ENTHALPY SAT VAPOR AT T2 = ";H2;"MJ/KG"
412 PRINT"ENTHALPY SAT WATER AT T2 = ";HF;"MJ/KG"
414 PRINT"SAT VAPOR PRESSURE AT T2 = ";PV;"BARS"
420 PRINT""
422 PRINT "DRY GAS ANALYSIS"
431 PRINT "%CO  =";X1
432 PRINT "%H2  =";X2
433 PRINT "%CH4 =";X3
435 PRINT "%C2H6=";X4
437 PRINT "%CO2 =";X5
438 PRINT "%O2  =";X6
440 PRINT "%N2  =";X7
442 PRINT "%H2O =";X8
444 PRINT A$
446 PRINT"OUTPUT DATA"
448 PRINT A$
450 PRINT"WET GAS ANALYSIS"
454 PRINT"%CO  =";Y1
456 PRINT"%H2  =";Y2
458 PRINT"%CH4 =";Y3
460 PRINT"%C2H6=";Y4
462 PRINT"%CO2 =";Y5
464 PRINT"%O2  =";Y6
466 PRINT"%N2  =";Y7
468 PRINT"%H2O =";Y8
470 PRINT""
496 T1=T1+273:REM CONVERT TO DEG K
497 T2=T2+273:REM CONVERT TO DEG K
498 REM LINES 500-540 CALCULATE AVG CP FROM T1-T2.THE CONSTANTS ARE FROM TABLE
499 REM 1.2,"PHYSICAL CHEMISTRY",4TH ED,BY DANIELS AND ALBERTY,JOHN WILEY,1975.
500 DIM A(8),B(8),C(8)
502 FOR I = 1 TO 8
504 READ A(I),B(I),C(I)
509 NEXT I
520 DATA 6.3424,1.8363E-3,-2.801E-7
522 DATA 6.9469,-.1999E-3,4.808E-7
524 DATA 3.422,17.845E-3,-41.65E-7
526 DATA 1.375,41.852E-3,-138.27E-7
528 DATA 6.3957,10.1933E-3,-35.333E-7
530 DATA 6.0954,3.2533E-3,-10.171E-7
532 DATA 6.4492,1.4125E-3,-.807E-7
534 DATA 7.1873,2.3733E-3,2.084E-7
540 REM LINE 542 CALCULATES MD,THE MOLECULAR WT OF DRY GAS
542 MD=(X1*28+X2*2+X3*16+X4*30+X5*44+X6*32+X7*28)/100
544 REM LINE 546 CALCULATES MW,THE MOLECULAR WT OF WET GAS
546 MW=(Y1*28+Y2*2+Y3*16+Y4*30+Y5*44+Y6*32+Y7*28+Y8*18)/100
548 REM LINE 550 CALCULATES MG,THE FLOW OF DRY GAS IN KG/HR
550 MG=GS*60*(1-(X8/100))*(1/22.4)*MD
```

```
 552 REM W1=KG H2O/KG DRY GAS AT T1
 554 W1=(Y8*18)/(MD*100)
 556 REM W2=KG H2O/KG DRY GAS AT T2
 558 W2=(PV/(1.014-PV))*18/MD
 560 REM LINES 562-580 CALCULATE HG, THE CHANGE IN ENTHALPY,DRY GAS,T1-T2
 562 DT=T1-T2:DS=T1↑2-T2↑2:DQ=T1↑3-T2↑3
 564 G1=(X1*(A(1)*DT+(B(1)/2)*DS+(C(1)/3)*DQ))/100
 566 G2=(X2*(A(2)*DT+(B(2)/2)*DS+(C(2)/3)*DQ))/100
 568 G3=(X3*(A(3)*DT+(B(3)/2)*DS+(C(3)/3)*DQ))/100
 570 G4=(X4*(A(4)*DT+(B(4)/2)*DS+(C(4)/3)*DQ))/100
 572 G5=(X5*(A(5)*DT+(B(5)/2)*DS+(C(5)/3)*DQ))/100
 574 G6=(X6*(A(6)*DT+(B(6)/2)*DS+(C(6)/3)*DQ))/100
 576 G7=(X7*(A(7)*DT+(B(7)/2)*DS+(C(7)/3)*DQ))/100
 578 HG=G1+G2+G3+G4+G5+G6+G7:REM HG IN GM-CAL/GM-MOLE
 580 HG=HG*4.1854E-3/MD:REM HG IN MJ/KG
 582 REM QC=HEAT REMOVED BY A CONDENSER OPERATING BTWN T1-T2
 584 REM SEE EQN 10-59,J.P.HOLMAN,"THERMODYNAMICS",THIRD EDITION
 586 QC=MG*(HG+(W1*H1-W2*H2)-((W1-W2)*HF))
 588 REM LINES 590-620 CALCULATE SH,THE SPECIFIC HEAT OF WET GAS AT T1
 589 REM RELATIVE TO 0 DEG C
 590 DT=T1-273:DS=T1↑2-273↑2:DQ=T1↑3-273↑3
 591 S1=(Y1*(A(1)*DT+(B(1)/2)*DS+(C(1)/3)*DQ))/100
 592 S2=(Y2*(A(2)*DT+(B(2)/2)*DS+(C(2)/3)*DQ))/100
 593 S3=(Y3*(A(3)*DT+(B(3)/2)*DS+(C(3)/3)*DQ))/100
 594 S4=(Y4*(A(4)*DT+(B(4)/2)*DS+(C(4)/3)*DQ))/100
 595 S5=(Y5*(A(5)*DT+(B(5)/2)*DS+(C(5)/3)*DQ))/100
 596 S6=(Y6*(A(6)*DT+(B(6)/2)*DS+(C(6)/3)*DQ))/100
 597 S7=(Y7*(A(7)*DT+(B(7)/2)*DS+(C(7)/3)*DQ))/100
 598 S8=(Y8*(A(8)*DT+(B(8)/2)*DS+(C(8)/3)*DQ))/100
 606 SH=S1+S2+S3+S4+S5+S6+S7+S8:REM SH IN GM-CAL/GM-MOLE
 608 REM SH(MJ/HR)=SH(GM-CAL/GM-MOLE)*(4.1854 J/GM-CAL)*(MJ/10E6 J)
 610 REM *(10E3 GM-MOLE/KG-MOLE)*(GS M3/MIN)*(1/22.4 M3/KG-MOLE)*(60 MIN/HR)
 620 SH=SH*(4.1854E-3)*GS*(1/22.4)*60
 622 PRINT"HEAT LOSS CONDENSERS  = ";FNX(QC);"MJ/HR"
 644 PRINT"SENSIBLE HEAT WET GAS = ";FNX(SH);"MJ/HR"
 646 PRINT""
 648 PRINT A$
 650 PRINT#4:CLOSE 4
 652 END
READY.
```

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```
-----------------------------------------------------------
GAS SENSIBLE & LATENT HEAT
RUN # 6
-----------------------------------------------------------
INPUT DATA
-----------------------------------------------------------
GAS FLOW = .77 M3/MIN
GAS TEMP = 197.8 DEG C
COND TEMP= 13.6 DEG C
ENTHALPY SAT VAPOR AT T1 =  2.7917 MJ/KG
ENTHALPY SAT VAPOR AT T2 =  2.5264 MJ/KG
ENTHALPY SAT WATER AT T2 =  .05711 MJ/KG
SAT VAPOR PRESSURE AT T2 =  .02161 BARS

DRY GAS ANALYSIS
%CO  = 20.7
%H2  = 16.5
%CH4 = 4.8
%C2H6= .2
%CO2 = 11.3
%O2  = 0
%N2  = 46.5
%H2O = 10.51
-----------------------------------------------------------
OUTPUT DATA
-----------------------------------------------------------
WET GAS ANALYSIS
%CO  = 18.5
%H2  = 14.8
%CH4 = 4.3
%C2H6= .2
%CO2 = 10.1
%O2  = 0
%N2  = 41.6
%H2O = 10.51

HEAT LOSS CONDENSERS  =  18.4 MJ/HR
SENSIBLE HEAT WET GAS =  12.83 MJ/HR

-----------------------------------------------------------
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```
---------------------------------------------------------
GAS  SENSIBLE  &  LATENT  HEAT
RUN  #  8
---------------------------------------------------------
INPUT DATA
---------------------------------------------------------
GAS FLOW = .63 M3/MIN
GAS TEMP = 214.2 DEG C
COND TEMP= 12.1 DEG C
ENTHALPY SAT VAPOR AT T1 =  2.8 MJ/KG
ENTHALPY SAT VAPOR AT T2 =  2.5236 MJ/KG
ENTHALPY SAT WATER AT T2 =  .05082 MJ/KG
SAT VAPOR PRESSURE AT T2 =  .01971 BARS

DRY GAS ANALYSIS
%CO  = 16.5
%H2  = 12.5
%CH4 = 1.9
%C2H6= .1
%CO2 = 8.5
%O2  = 2.4
%N2  = 58.1
%H2O = 10.56
---------------------------------------------------------
OUTPUT DATA
---------------------------------------------------------
WET GAS ANALYSIS
%CO  = 14.8
%H2  = 11.2
%CH4 = 1.7
%C2H6= .1
%CO2 = 7.6
%O2  = 2.1
%N2  = 52
%H2O = 10.56

HEAT LOSS CONDENSERS  =  15.78 MJ/HR
SENSIBLE HEAT WET GAS =  11.09 MJ/HR

---------------------------------------------------------
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```
-----------------------------------------------------------
GAS  SENSIBLE  &  LATENT  HEAT
RUN  #  11
-----------------------------------------------------------
INPUT DATA
-----------------------------------------------------------
GAS FLOW = .75 M3/MIN
GAS TEMP = 197.6 DEG C
COND TEMP= 9.4 DEG C
ENTHALPY SAT VAPOR AT T1 =  2.7916 MJ/KG
ENTHALPY SAT VAPOR AT T2 =  2.5187 MJ/KG
ENTHALPY SAT WATER AT T2 =  .03949 MJ/KG
SAT VAPOR PRESSURE AT T2 =  .01185 BARS

DRY GAS ANALYSIS
%CO  = 20.9
%H2  = 14.5
%CH4 = 2.3
%C2H6= .1
%CO2 = 11.9
%O2  = .3
%N2  = 50
%H2O = 14.15
-----------------------------------------------------------
OUTPUT DATA
-----------------------------------------------------------
WET GAS ANALYSIS
%CO  = 17.9
%H2  = 12.4
%CH4 = 2
%C2H6= .1
%CO2 = 10.2
%O2  = .3
%N2  = 42.9
%H2O = 14.15

HEAT LOSS CONDENSERS  =  21.16 MJ/HR
SENSIBLE HEAT WET GAS =  12.37 MJ/HR

-----------------------------------------------------------
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```
-----------------------------------------------------------
GAS SENSIBLE & LATENT HEAT
RUN # 12
-----------------------------------------------------------
INPUT DATA
-----------------------------------------------------------
GAS FLOW = .74 M3/MIN
GAS TEMP = 180.6 DEG C
COND TEMP= 4.1 DEG C
ENTHALPY SAT VAPOR AT T1 =  2.7787 MJ/KG
ENTHALPY SAT VAPOR AT T2 =  2.5089 MJ/KG
ENTHALPY SAT WATER AT T2 =  .0172 MJ/KG
SAT VAPOR PRESSURE AT T2 =  8.25E-03 BARS

DRY GAS ANALYSIS
%CO  = 21.5
%H2  = 13.7
%CH4 = 2.5
%C2H6= .1
%CO2 = 11
%O2  = .3
%N2  = 50.9
%H2O = 12.31
-----------------------------------------------------------
OUTPUT DATA
-----------------------------------------------------------
WET GAS ANALYSIS
%CO  = 18.9
%H2  = 12
%CH4 = 2.2
%C2H6= .1
%CO2 = 9.6
%O2  = .3
%N2  = 44.6
%H2O = 12.31

HEAT LOSS CONDENSERS  =  19.27 MJ/HR
SENSIBLE HEAT WET GAS =  11.03 MJ/HR

-----------------------------------------------------------
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# APPENDIX C

## COMPUTER PROGRAM "ENERGY"

Computer program "ENERGY" is written in the BASIC language for the Commodore PET 2001 mini-computer. The program uses the dry gas analysis, gas moisture content, wet fuel rate, dry fuel energy, air flow, wet gas flow, gas energy content (computed by program "GASEN"), gas moisture content, char rate, char energy, condensate rate, condensate energy, gas sensible heat and condenser energy loss (computed by program "GASHEAT"), to calculate an energy balance. A listing of the program and printouts for the experimental runs are attached. Remark statements (REM) are used throughout the program as comments to the user. Program variables are identified in INPUT statements as they occur.

```
1 PRINT"⊐"
2 B$="****************************************"
3 PRINT B$
4 PRINT"ꝎꝎꝎꝎ"
6 PRINT"            PROGRAM ENERGY"
8 PRINT""
10 PRINT""
12 PRINT"                 BY"
14 PRINT""
16 PRINT""
18 PRINT"              SAM VIGIL"
20 PRINT""
22 PRINT""
23 PRINT"                10/11/80 "
24 PRINT""
25 PRINT"     REV  12/20/80, 2/17/81"
26 PRINT"Ꝏ"
28 PRINT B$
30 FORI=1TO5000:NEXT:PRINT"⊐"
32 PRINT B$
34 PRINT"ꝎꝎ"
36 PRINT"PROGRAM ENERGY COMPUTES AN ENERGY":PRINT""
38 PRINT"BALANCE FOR THE UCD SLUDGE GASIFIER.":PRINT""
40 PRINT"ꝎꝎꝎꝎ"
42 PRINT"PLEASE SEE THE PROGRAM LISTING FOR":PRINT""
44 PRINT"DETAILED INFORMATION.
46 PRINT"ꝎꝎꝎ"
48 PRINT B$
50 FOR I=1TO8000:NEXT:PRINT"⊐"
52 REM LINES 1-50 SET UP TITLES
60 PRINT"≋ENTER RUN ID #"
65 INPUT RU
100 PRINT"≋ENTER WET FUEL RATE, KG/HR"
110 INPUT WF
120 PRINT"≋ENTER FUEL MOIST %"
130 INPUT MC
140 PRINT"≋ENTER DRY FUEL ENERGY CONTENT MJ/KG"
150 INPUT FE
160 PRINT"≋ENTER LHV DRY GAS (0 DEG C,30 IN HG) MJ/M3"
170 INPUT GE
180 PRINT"≋ENTER GAS MOIST %"
190 INPUT GM
192 PRINT"≋ENTER AIR FLOW RATE M3/MIN AT 0 DEG C,1 ATM"
193 INPUT GA
200 PRINT"≋ENTER WET GAS FLOW RATE M3/MIN AT 0 DEG C,1 ATM"
210 INPUT GF
212 PRINT"⊐"
220 PRINT"≋ENTER GAS SENS HEAT MJ/HR"
230 INPUT GS
232 PRINT"≋ENTER HEAT LOSS CONDENSER MJ/HR"
234 INPUT QC
240 PRINT"≋ENTER CHAR ENERGY MJ/KG"
250 INPUT C1
260 PRINT"≋ENTER CHAR RATE KG/HR"
270 INPUT C2
280 PRINT"≋ENTER COND RATE KG/HR"
281 INPUT C3
282 REM COND ENERGY = 4.75 MJ/KG
283 PRINT"⊐"
290 PRINT"ENTER FUEL DRY ULTIMATE ANALYSIS":PRINT""
300 PRINT"≋ENTER %C"
310 INPUT CR
```

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```
330 PRINT"▒ENTER %H"
340 INPUT HR
360 PRINT"▒ENTER %N"
370 INPUT NR
374 PRINT"▒ENTER %S"
376 INPUT SR
390 PRINT"▒ENTER %O"
400 INPUT OX
450 PRINT"▒ENTER %RESIDUE"
460 INPUT RR
470 PRINT"J"
471 OPEN 3,4
472 CMD 3
480 A$="--------------------------------------------------------"
490 PRINT A$
510 PRINT CHR$(1)" ENERGY BALANCE RUN #";RU
530 PRINT A$
550 PRINT"RUN #";RU
560 PRINT"WET FUEL RATE ";WF;"KG/HR"
570 PRINT"FUEL MOISTURE ";MC;"%"
580 PRINT"DRY FUEL ENERGY ";FE;"MJ/KG"
581 PRINT"AIR FLOW IN";GA;"M3/MIN"
590 PRINT"WET GAS FLOW RATE (SAT)";GF;"M3/MIN"
600 PRINT"LHV DRY GAS (0 DEG C,30 IN HG)";GE;"MJ/M3"
601 PRINT"GAS MOISTURE CONTENT";GM;"%"
610 PRINT"CHAR RATE";C2;"KG/HR"
611 PRINT"CHAR ENERGY";C1;"MJ/KG"
620 PRINT"COND RATE";C3;"KG/HR"
630 PRINT"COND ENERGY = 4.75 MJ/KG"
640 PRINT A$
650 CF=CR*100/(100-RR):REM %C RESIDUE FREE BASIS
660 HF=HR*100/(100-RR):REM %H RESIDUE FREE BASIS
670 NF=NR*100/(100-RR):REM %N RESIDUE FREE BASIS
680 O1=OX*100/(100-RR):REM %O RESIDUE FREE BASIS
690 SF=SR*100/(100-RR):REM %S RESIDUE FREE BASIS
700 DEF FNR(X)=INT(X*100+.5)/100:REM ROUND OFF FUNCTION TO 0.01
710 PRINT"FUEL ANALYSES"
720 PRINT" ","DRY ULT","DRY ULT","STOICH"
730 PRINT" "," ","RES FREE","CONST"
740 CS=CF/12:REM STOICHIOMETRIC CONST C (RESIDUE FREE BASIS)
750 HS=HF:REM    STOICHIOMETRIC CONST H (RESIDUE FREE BASIS)
760 OS=O1/16:REM STOICHIOMETRIC CONST O (RESIDUE FREE BASIS)
770 PRINT"%C",    CR ,FNR(CF),FNR(CS)
780 PRINT"%H",    HR ,FNR(HF),FNR(HS)
790 PRINT"%O",    OX ,FNR(O1),FNR(OS)
800 PRINT"%N",    NR ,FNR(NF)
810 PRINT"%S",    SR ,FNR(SF)
820 PRINT"%RES",    RR
830 PRINT A$
840 EG=WF*((100-MC)/100)*FE:REM GROSS ENERGY DRY FUEL
842 IF HR-(OX/8)<=0 THEN 854:REM TESTS H/O RATIO IN FUEL
846 BW=OX+(OX/8):REM BW=BOUND WATER %, EXCESS H
850 GOTO 860
854 BW=9*HR:REM BW=BOUND WATER %,H LIMITED,EXCESS O
860 BW=BW/100:REM BW=BOUND WATER FRACTION
862 EL=WF*BW*((100-MC)/100)*2.257:REM   LATENT HEAT IN BOUND WATER
880 REM 862&890 ASSUME LH H20 = 2.257 MJ/KG AT 1 ATM,100 DEG C
890 EM=WF*MC*2.257/100:REM LATENT HEAT IN M/C OF FUEL
900 EN=EG-EL-EM:REM NET ENERGY IN DRY FUEL
910 EC=GF*((100-GM)/100)*GE*60:REM CHEMICAL ENERGY IN SATURATED GAS
920 E1=C1*C2:REM ENERGY OUT CHAR
930 E2=C3*4.75:REM ENERGY OUT CONDENSATE
940 REM 930 ASSUMES COND = 4.75 MJ/KG
950 E3=EC+GS:REM ENERGY OUT HOT GAS (INCL SENSIBLE HEAT GAS)
951 LO=EN-EC-GS-QC-E1-E2
952 REM LO=ENERGY LOSSES=(NET EN FUEL)-(CHEM EN GAS)-(SENS EN GAS)-(HEAT LOSS
 953 REM CONDENSER)-(EN LOSS CHAR)-(EN LOSS CONDENSATE)
 960 PRINT"ENERGY BALANCE"
 961 PRINT"GROSS ENERGY,DRY FUEL = ";FNR(EG);"MJ/HR"
 980 PRINT"LATENT HEAT,COMB H2O  = ";FNR(EL);"MJ/HR"
 990 PRINT"LATENT HEAT,MOIST     = ";FNR(EM);"MJ/HR"
 991 PC=(EC/EN)*100
 992 PS=(GS/EN)*100
 993 P1=(E1/EN)*100
 994 P2=(E2/EN)*100
 995 PL=(LO/EN)*100
 996 PQ=(QC/EN)*100
 1000 PRINT"NET ENERGY,DRY FUEL      = ";FNR(EN);"MJ/HR  100%"
 1010 PRINT"CHEM ENERGY,GAS       = ";FNR(EC);"MJ/HR";FNR(PC);"%"
 1020 PRINT"SENS ENERGY,GAS       = ";FNR(GS);"MJ/HR";FNR(PS);"%"
 1025 PRINT"HEAT LOSS CONDENSER  = ";FNR(QC);"MJ/HR";FNR(PQ);"%"
 1030 PRINT"ENERGY OUT,CHAR       = ";FNR(E1);"MJ/HR";FNR(P1);"%"
 1040 PRINT"ENERGY OUT,CONDENSATE= ";FNR(E2);"MJ/HR";FNR(P2);"%"
 1050 PRINT"ENERGY LOSSES         = ";FNR(LO);"MJ/HR";FNR(PL);"%"
 1060 PRINT A$
 1061 XX=EC+GS
 1070 PRINT"HOT GAS OUT = ";FNR(XX);"MJ/HR"
 1080 PRINT"COLD GAS OUT = ";FNR(EC);"MJ/HR"
 1090 HG=(XX/EN)*100
 1100 PRINT"HOT GAS EFF = ";FNR(HG);"%"
 1110 CG=(EC/EN)*100
 1120 PRINT"COLD GAS EFF = ";FNR(CG);"%"
 1130 PRINT A$
 1240 AA=(11.53*CR+34.34*(HR-(OX/8))+4.29*SR)/100
 1250 REM AA=STOICH AIR REQMT KG AIR/KG DRY FUEL
 1260 REM DENSITY DRY AIR = 1.384 KG/M3
 1270 AS=AA*(WF*(100-MC)/100)*(1/60)*(1/1.384):REM STOICH AIR M3/MIN
 1280 AR=(GA/AS)*100:REM GASIFICATION AIR/STOICHIOMETRIC AIR
 1290 PRINT"STOICH AIR = ";FNR(AA);" KG AIR/KG DRY FUEL"
 1300 PRINT"STOICH AIR = ";FNR(AS); "M3/MIN"
 1301 AG=GA*60*1.384/(WF*(100-MC)/100):REM GASIFICATION AIR/KG DRY FUEL
 1302 PRINT"GASIFICATION AIR = ";FNR(AG);"KG AIR/KG DRY FUEL"
 1303 PRINT"GASIFICATION AIR = ";FNR(GA);"M3/MIN"
 1310 PRINT"GASIFICATION AIR = ";FNR(AR);"% STOICH"
 1320 PRINT A$
 1321 PRINT#3:CLOSE 3
 1330 END
READY.
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---------------------------------------------------------
  ENERGY BALANCE RUN # 6
---------------------------------------------------------
RUN # 6
WET FUEL RATE  27.2 KG/HR
FUEL MOISTURE  10.71 %
DRY FUEL ENERGY  19.06 MJ/KG
AIR FLOW IN .407 M3/MIN
WET GAS FLOW RATE (SAT) .773 M3/MIN
LHV DRY GAS (0 DEG C,30 IN HG) 6.26 MJ/M3
GAS MOISTURE CONTENT 10.51 %
CHAR RATE 2.8 KG/HR
CHAR ENERGY 19.39 MJ/KG
COND RATE .18 KG/HR
COND ENERGY = 4.75 MJ/KG
---------------------------------------------------------
FUEL ANALYSES
           DRY ULT          DRY ULT          STOICH
                      RES FREE          CONST
%C           45.58            47.73            3.98
%H           5.83            6.1           6.1
%O           43.92            45.99            2.87
%N           .17            .18
%S           0          0
%RES           4.5
---------------------------------------------------------
ENERGY BALANCE
GROSS ENERGY,DRY FUEL =  462.91 MJ/HR
LATENT HEAT,COMB H2O  =  27.08 MJ/HR
LATENT HEAT,MOIST     =  6.57 MJ/HR
NET ENERGY,DRY FUEL     =  429.25 MJ/HR  100%
CHEM ENERGY,GAS      =  259.82 MJ/HR 60.53 %
SENS ENERGY,GAS      =  12.83 MJ/HR 2.99 %
HEAT LOSS CONDENSER  =  18.4 MJ/HR 4.29 %
ENERGY OUT,CHAR      =  54.29 MJ/HR 12.65 %
ENERGY OUT,CONDENSATE=  .86 MJ/HR .2 %
ENERGY LOSSES        =  83.05 MJ/HR 19.35 %
---------------------------------------------------------
HOT GAS OUT =  272.65 MJ/HR
COLD GAS OUT =  259.82 MJ/HR
HOT GAS EFF =  63.52 %
COLD GAS EFF =  60.53 %
---------------------------------------------------------
STOICH AIR =  5.37  KG AIR/KG DRY FUEL
STOICH AIR =  1.57 M3/MIN
GASIFICATION AIR =  1.39 KG AIR/KG DRY FUEL
GASIFICATION AIR =  .41 M3/MIN
GASIFICATION AIR =  25.9 % STOICH
---------------------------------------------------------
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--------------------------------------------------------
 ENERGY BALANCE RUN # 8
--------------------------------------------------------
RUN # 8
WET FUEL RATE  22.8 KG/HR
FUEL MOISTURE  5.51 %
DRY FUEL ENERGY  18.92 MJ/KG
AIR FLOW IN .412 M3/MIN
WET GAS FLOW RATE (SAT) .627 M3/MIN
LHV DRY GAS (0 DEG C,30 IN HG) 4.19 MJ/M3
GAS MOISTURE CONTENT 10.56 %
CHAR RATE 2.5 KG/HR
CHAR ENERGY 8.52 MJ/KG
COND RATE .6 KG/HR
COND ENERGY = 4.75 MJ/KG
--------------------------------------------------------
FUEL ANALYSES
           DRY ULT          DRY ULT          STOICH
                      RES FREE          CONST
%C           44.37           46.12            3.84
%H           5.62            5.84            5.84
%O           45.9            47.71            2.98
%N           .26             .27
%S           .05             .05
%RES           3.8
--------------------------------------------------------
ENERGY BALANCE
GROSS ENERGY,DRY FUEL =  407.61 MJ/HR
LATENT HEAT,COMB H2O  =  24.59 MJ/HR
LATENT HEAT,MOIST     =  2.84 MJ/HR
NET ENERGY,DRY FUEL      =  380.18 MJ/HR  100%
CHEM ENERGY,GAS      =  140.98 MJ/HR 37.08 %
SENS ENERGY,GAS      =  11.09 MJ/HR 2.92 %
HEAT LOSS CONDENSER  =  15.78 MJ/HR 4.15 %
ENERGY OUT,CHAR      =  21.3 MJ/HR 5.6 %
ENERGY OUT,CONDENSATE=  2.85 MJ/HR .75 %
ENERGY LOSSES        =  188.18 MJ/HR 49.5 %
--------------------------------------------------------
HOT GAS OUT =  152.07 MJ/HR
COLD GAS OUT =  140.98 MJ/HR
HOT GAS EFF =  40 %
COLD GAS EFF =  37.08 %
--------------------------------------------------------
STOICH AIR =  5.08  KG AIR/KG DRY FUEL
STOICH AIR =  1.32 M3/MIN
GASIFICATION AIR =  1.59 KG AIR/KG DRY FUEL
GASIFICATION AIR =  .41 M3/MIN
GASIFICATION AIR =  31.28 % STOICH
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--------------------------------------------------------
  ENERGY  BALANCE  RUN  #  11
--------------------------------------------------------
RUN # 11
WET FUEL RATE  17.5 KG/HR
FUEL MOISTURE  10.5 %
DRY FUEL ENERGY  18.93 MJ/KG
AIR FLOW IN .407 M3/MIN
WET GAS FLOW RATE (SAT) .749 M3/MIN
LHV DRY GAS (0 DEG C,30 IN HG) 5.11 MJ/M3
GAS MOISTURE CONTENT 14.15 %
CHAR RATE 2.5 KG/HR
CHAR ENERGY 27.6 MJ/KG
COND RATE .5 KG/HR
COND ENERGY = 4.75 MJ/KG
--------------------------------------------------------
FUEL ANALYSES
           DRY ULT          DRY ULT          STOICH
                      RES FREE         CONST
%C           45.24            46.12            3.84
%H           5.81            5.92            5.92
%O           46.81            47.72            2.98
%N           .13            .13
%S           .11            .11
%RES           1.91
--------------------------------------------------------
ENERGY BALANCE
GROSS ENERGY,DRY FUEL =  296.49 MJ/HR
LATENT HEAT,COMB H20  =  18.48 MJ/HR
LATENT HEAT,MOIST     =  4.15 MJ/HR
NET ENERGY,DRY FUEL      =  273.86 MJ/HR  100%
CHEM ENERGY,GAS      =  197.15 MJ/HR 71.99 %
SENS ENERGY,GAS      =  12.37 MJ/HR 4.52 %
HEAT LOSS CONDENSER  =  21.16 MJ/HR 7.73 %
ENERGY OUT,CHAR      =  69 MJ/HR 25.2 %
ENERGY OUT,CONDENSATE=  2.38 MJ/HR .87 %
ENERGY LOSSES        = -28.19 MJ/HR-10.3 %
--------------------------------------------------------
HOT GAS OUT =  209.52 MJ/HR
COLD GAS OUT =  197.15 MJ/HR
HOT GAS EFF =  76.51 %
COLD GAS EFF =  71.99 %
--------------------------------------------------------
STOICH AIR =  5.21  KG AIR/KG DRY FUEL
STOICH AIR =  .98 M3/MIN
GASIFICATION AIR =  2.16 KG AIR/KG DRY FUEL
GASIFICATION AIR =  .41 M3/MIN
GASIFICATION AIR =  41.44 % STOICH
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--------------------------------------------------------
  ENERGY  BALANCE  RUN  #  12
--------------------------------------------------------
RUN # 12
WET FUEL RATE  16.3 KG/HR
FUEL MOISTURE  11.05 %
DRY FUEL ENERGY  18.49 MJ/KG
AIR FLOW IN .415 M3/MIN
WET GAS FLOW RATE (SAT) .735 M3/MIN
LHV DRY GAS (0 DEG C,30 IN HG) 5.17 MJ/M3
GAS MOISTURE CONTENT 12.31 %
CHAR RATE 1.7 KG/HR
CHAR ENERGY 24.38 MJ/KG
COND RATE .7 KG/HR
COND ENERGY = 4.75 MJ/KG
--------------------------------------------------------
FUEL ANALYSES
           DRY ULT          DRY ULT          STOICH
                 RES FREE          CONST
%C           45.27            47.25            3.94
%H           5.77            6.02            6.02
%O           44.18            46.12            2.88
%N           .42            .44
%S           .16            .17
%RES           4.2
--------------------------------------------------------
ENERGY BALANCE
GROSS ENERGY,DRY FUEL =  268.08 MJ/HR
LATENT HEAT,COMB H2O  =  16.26 MJ/HR
LATENT HEAT,MOIST     =  4.07 MJ/HR
NET ENERGY,DRY FUEL      =  247.75 MJ/HR  100%
CHEM ENERGY,GAS       =  199.93 MJ/HR 80.7 %
SENS ENERGY,GAS       =  11.03 MJ/HR 4.45 %
HEAT LOSS CONDENSER   =  19.27 MJ/HR 7.78 %
ENERGY OUT,CHAR       =  41.45 MJ/HR 16.73 %
ENERGY OUT,CONDENSATE=  3.33 MJ/HR 1.34 %
ENERGY LOSSES         = -27.25 MJ/HR-11 %
--------------------------------------------------------
HOT GAS OUT =  210.96 MJ/HR
COLD GAS OUT =  199.93 MJ/HR
HOT GAS EFF =  85.15 %
COLD GAS EFF =  80.7 %
--------------------------------------------------------
STOICH AIR =  5.31  KG AIR/KG DRY FUEL
STOICH AIR =  .93 M3/MIN
GASIFICATION AIR =  2.38 KG AIR/KG DRY FUEL
GASIFICATION AIR =  .42 M3/MIN
GASIFICATION AIR =  44.75 % STOICH
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(PREVIOUSLY EIN. EPA FORM 387)

TYPING GUIDE SHEET